Jet quenching and the relation between $\hat{q}$ and the TMDPDF

Abhijit Majumder
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Jet quenching and the relation between $\hat{q}$ and the TMDPDF

And the resolution of the JET normalization puzzle

Abhijit Majumder
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POETIC 2016, Temple University, PA, Nov 14-16, 2016

Full jets versus leading hadrons

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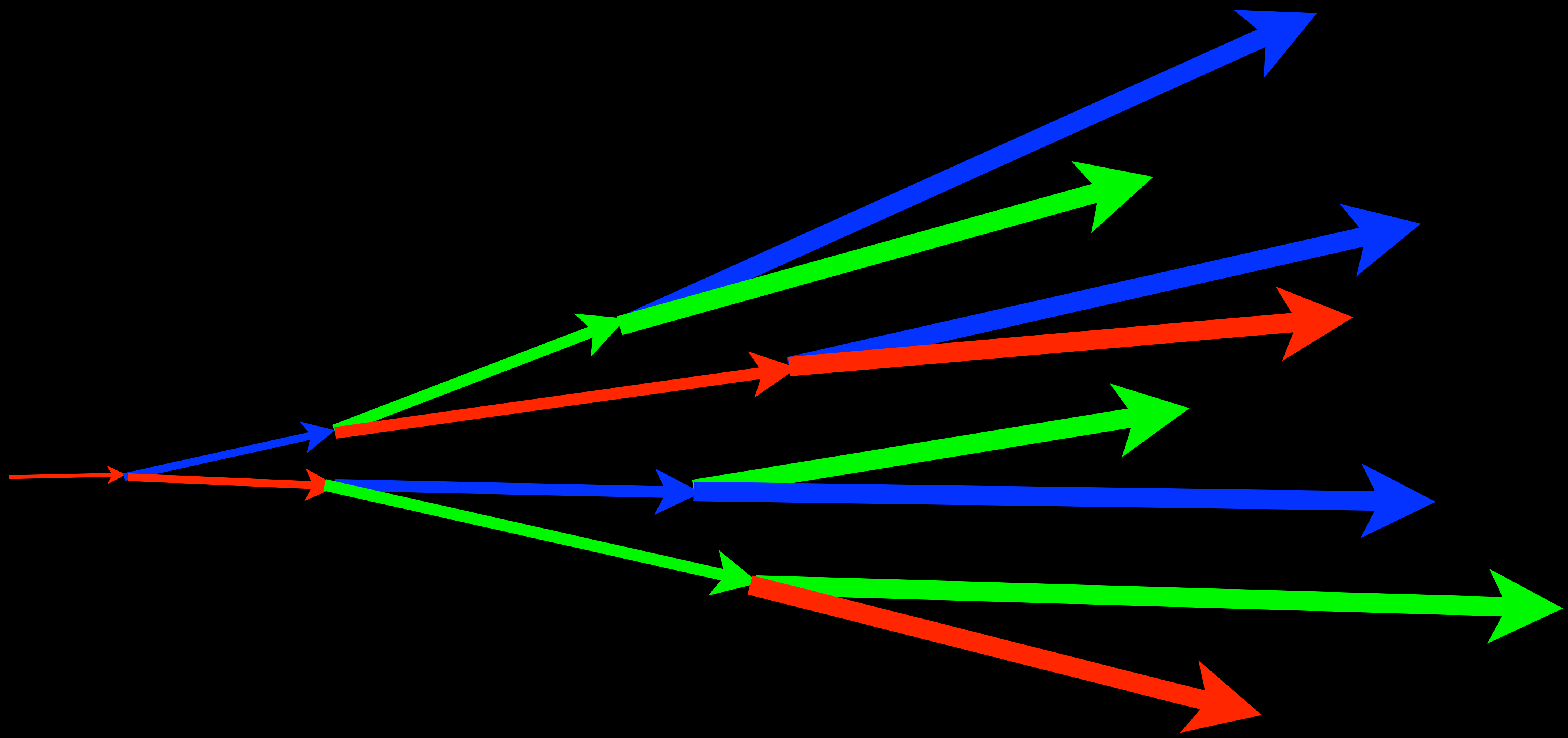

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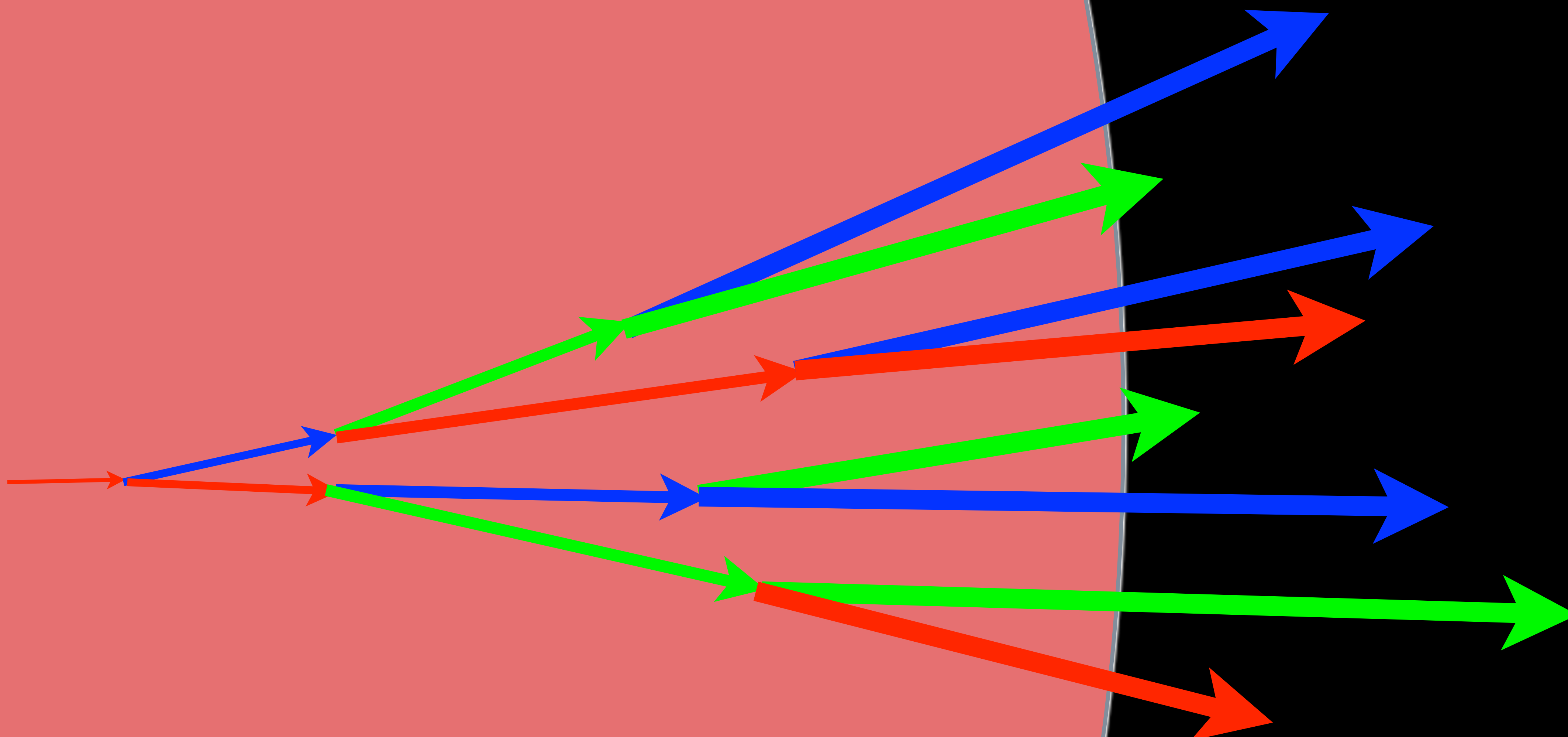

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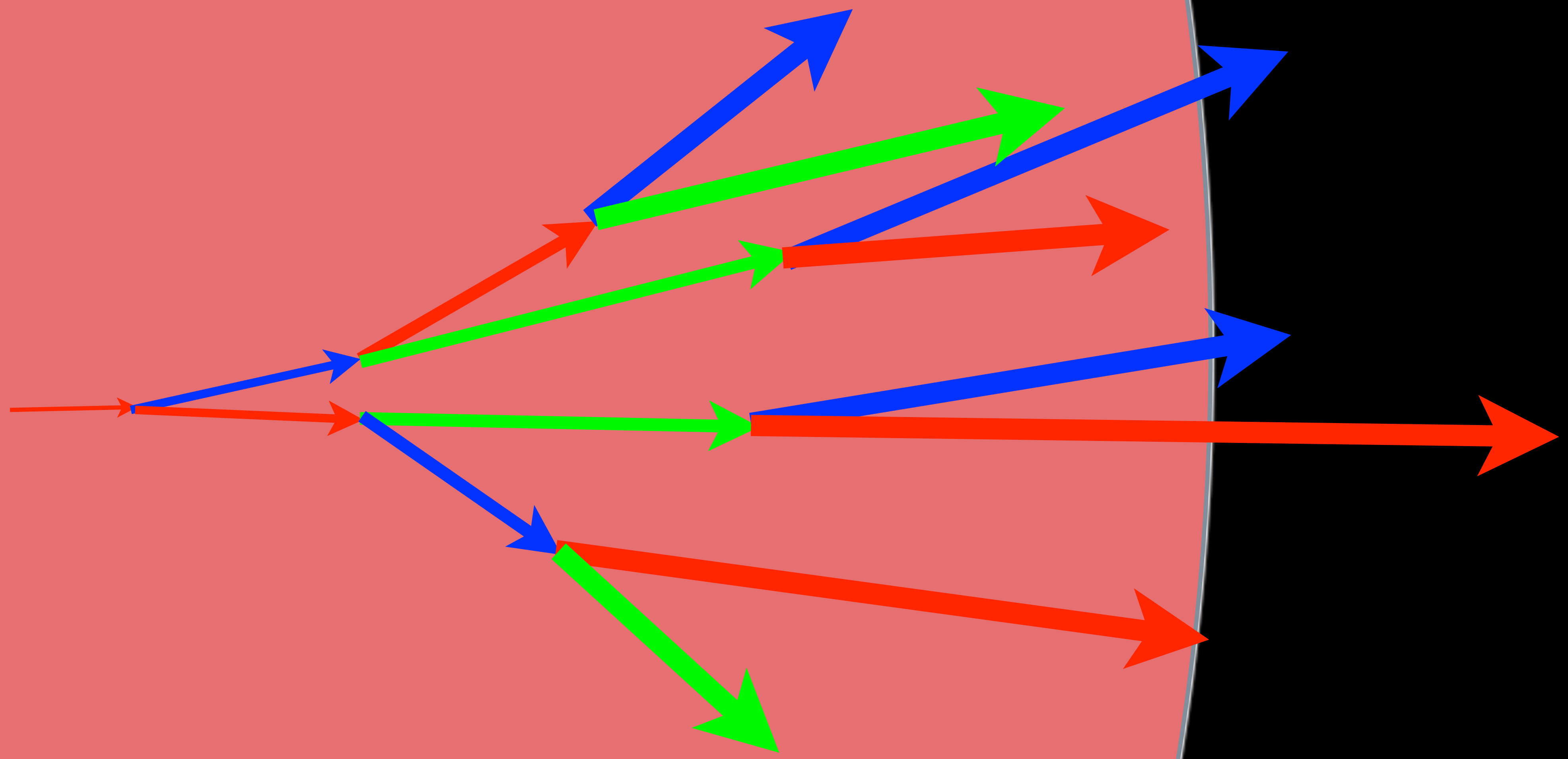

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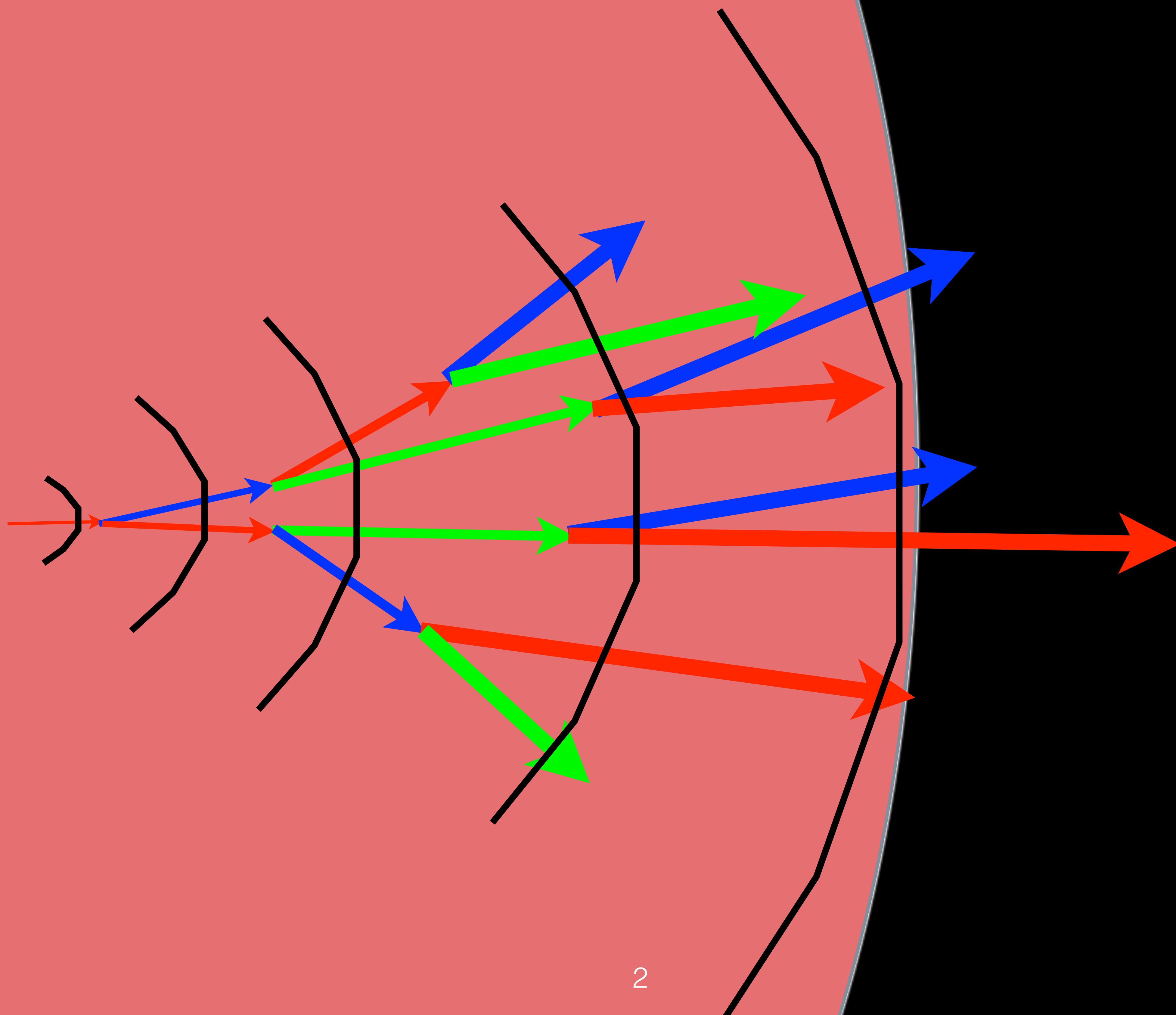

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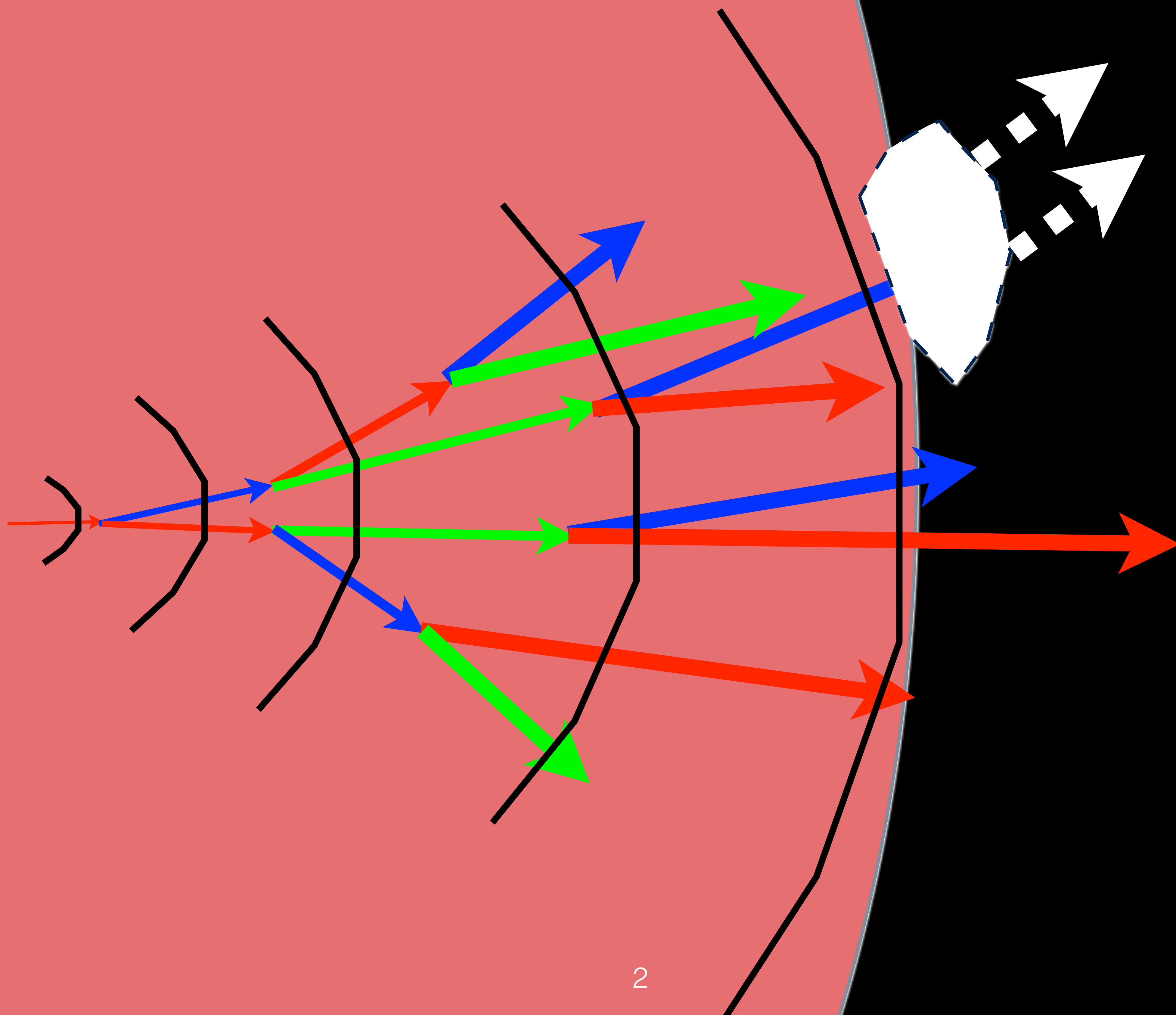

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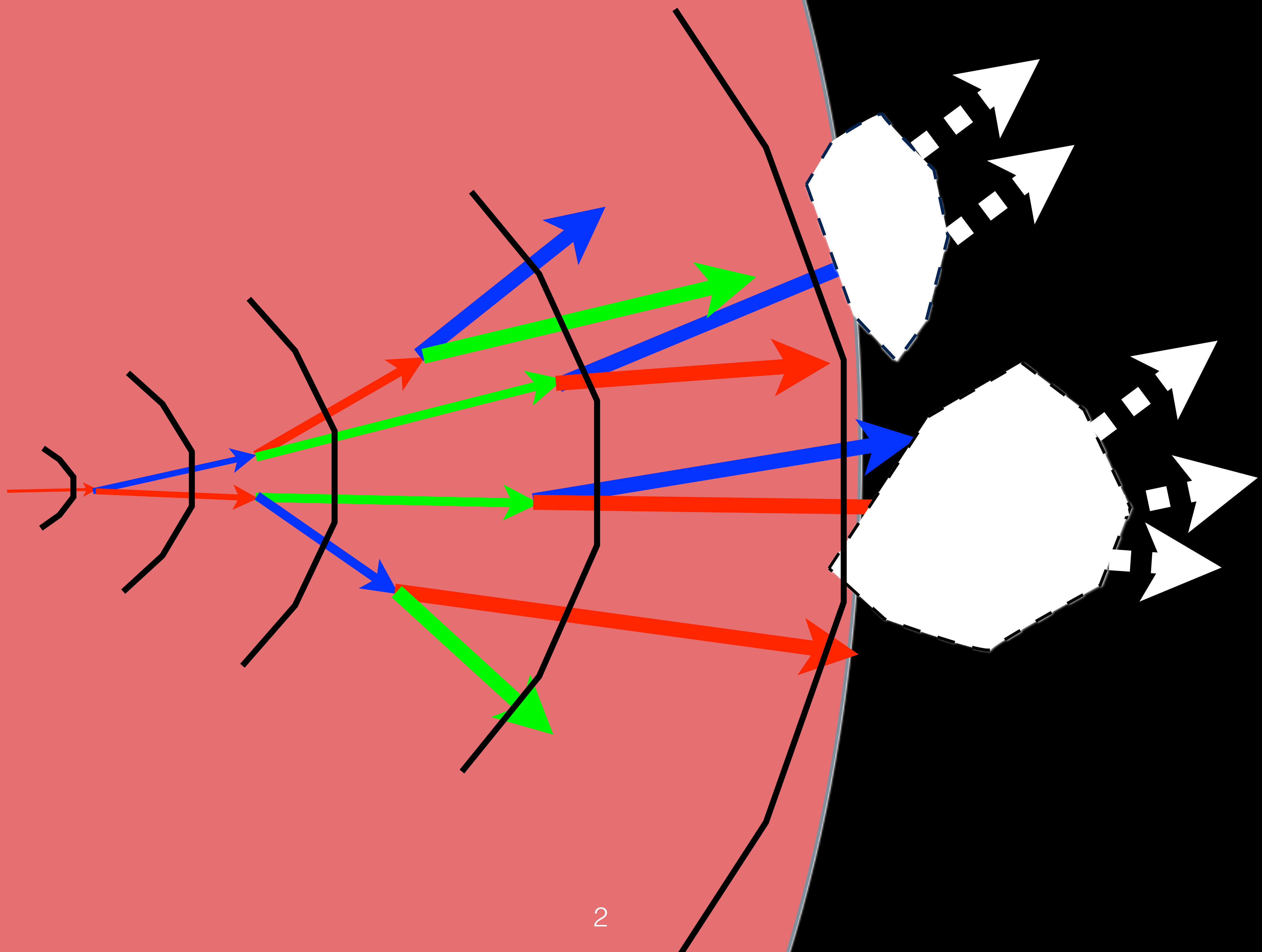
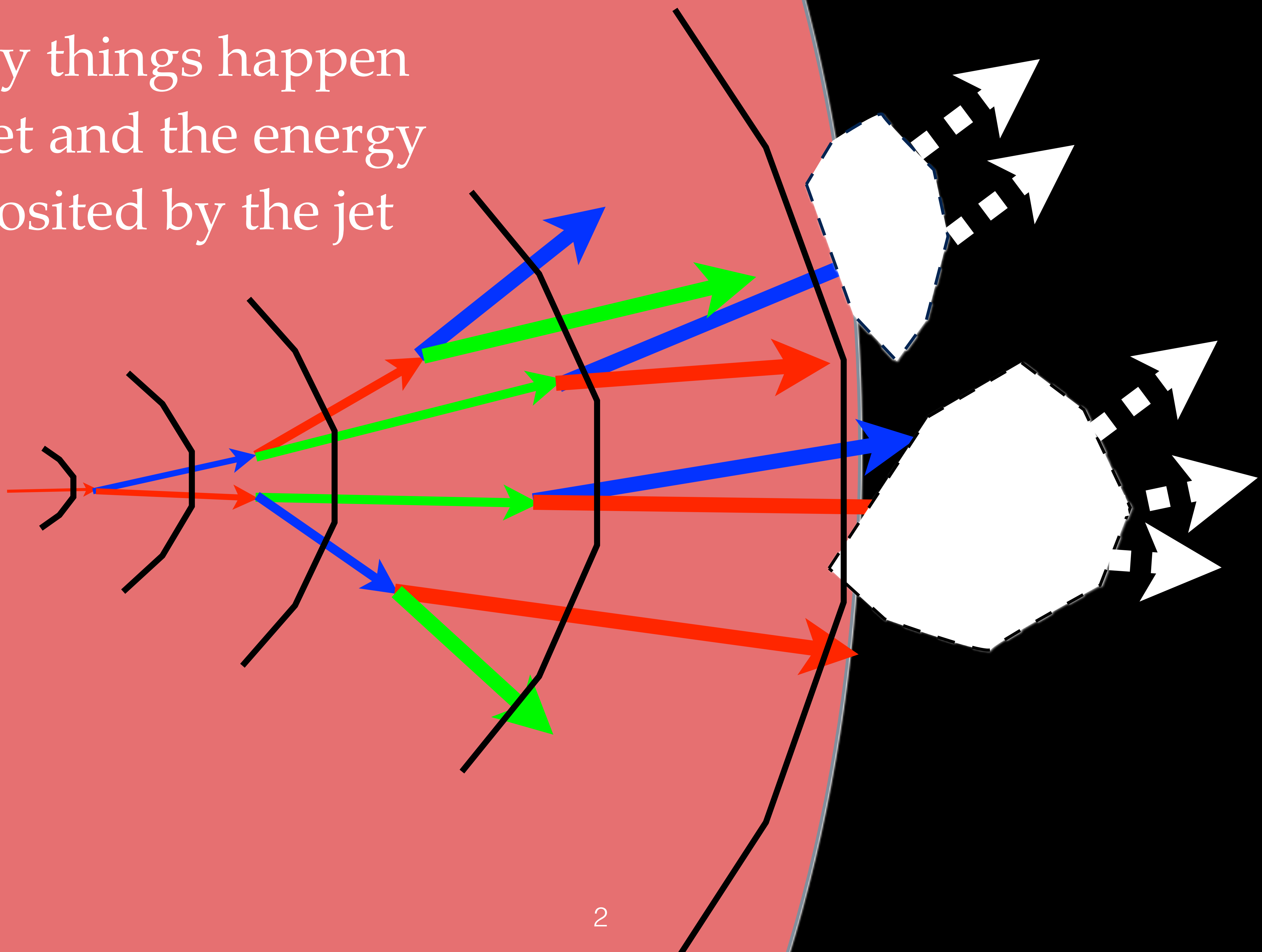


Full jets versus leading hadrons

Many things happen to a jet and the energy deposited by the jet



Full jets versus leading hadrons

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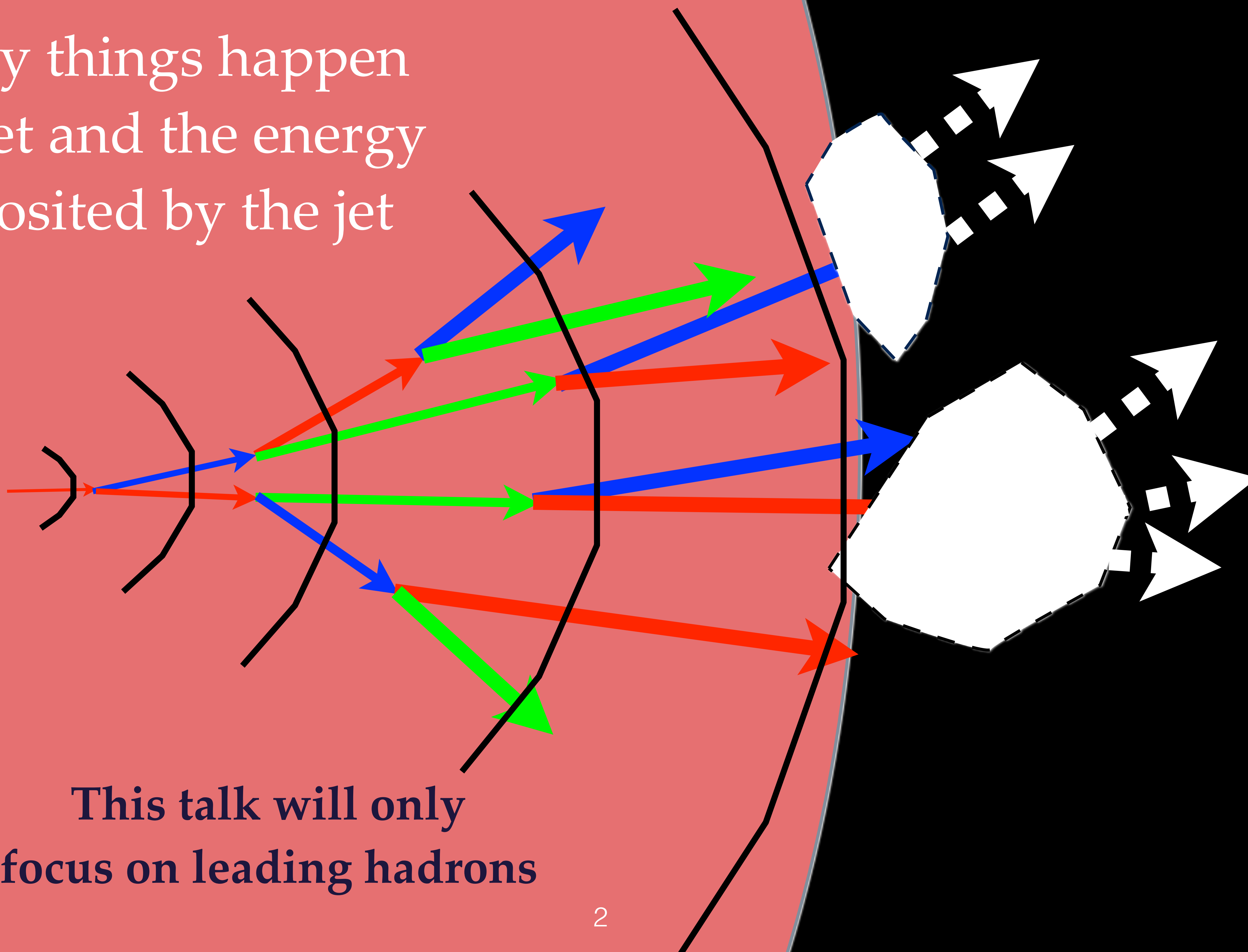
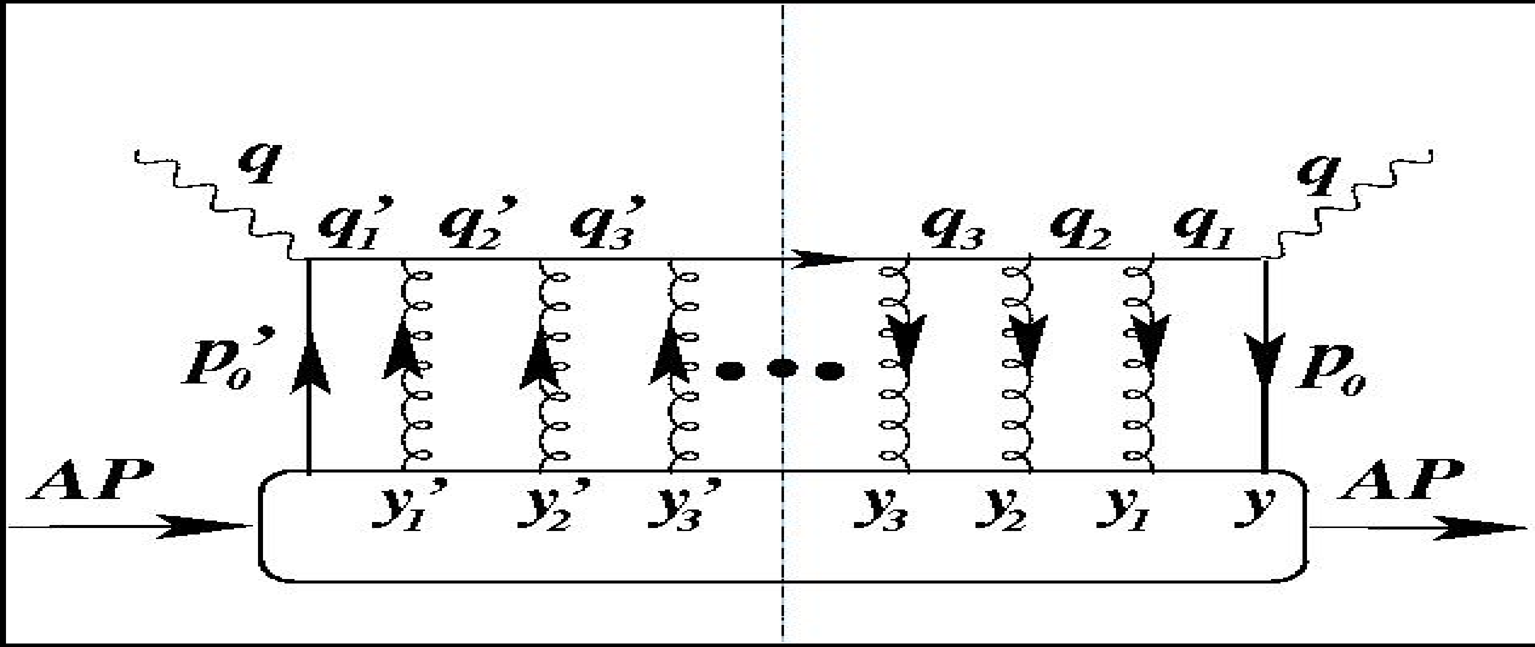


This talk will only focus on leading hadrons

Consider multiple scattering in DIS

The quark has momentum components

$q = (q^-, q^+, q_T) = (1, \lambda^2, \lambda)Q$, Q: Hard scale, $\lambda \ll 1$, $\lambda Q \gg \Lambda_{QCD}$



hence, gluons have

$$k_\perp \sim \lambda Q, \qquad k^+ \sim \lambda^2 Q$$

Called Glauber gluons

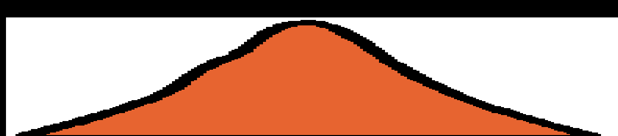
A.M. & B. Mueller Phys.Rev. C77 (2008) 054903

Assuming the medium has a large length.

Or, the parton has a long life time, $1/(\lambda^2 Q)$

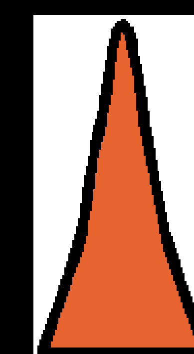
Multiple independent scattering dominates over multiple correlated scattering

Re-summing gives a diffusion equation for the p_T distribution



$$\frac{\partial f(p_\perp, t)}{\partial t} = \nabla_{p_\perp} \cdot D \cdot \nabla_{p_\perp} f(p_\perp, t)$$

$$\langle p_\perp^2 \rangle = 4Dt$$



$$\hat{q} = \frac{p_\perp^2}{t} = \frac{2\pi^2 \alpha_s C_R}{N_c^2 - 1} \int d\tilde{t} \left\langle F^{\mu\alpha}(\tilde{t}) v_\alpha F^{\beta}_{\mu}(0) v_\beta \right\rangle$$

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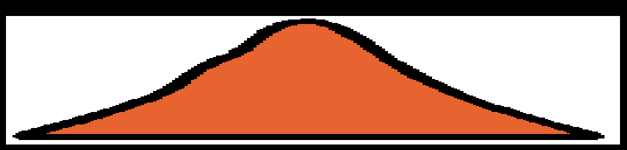

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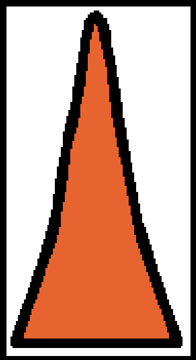
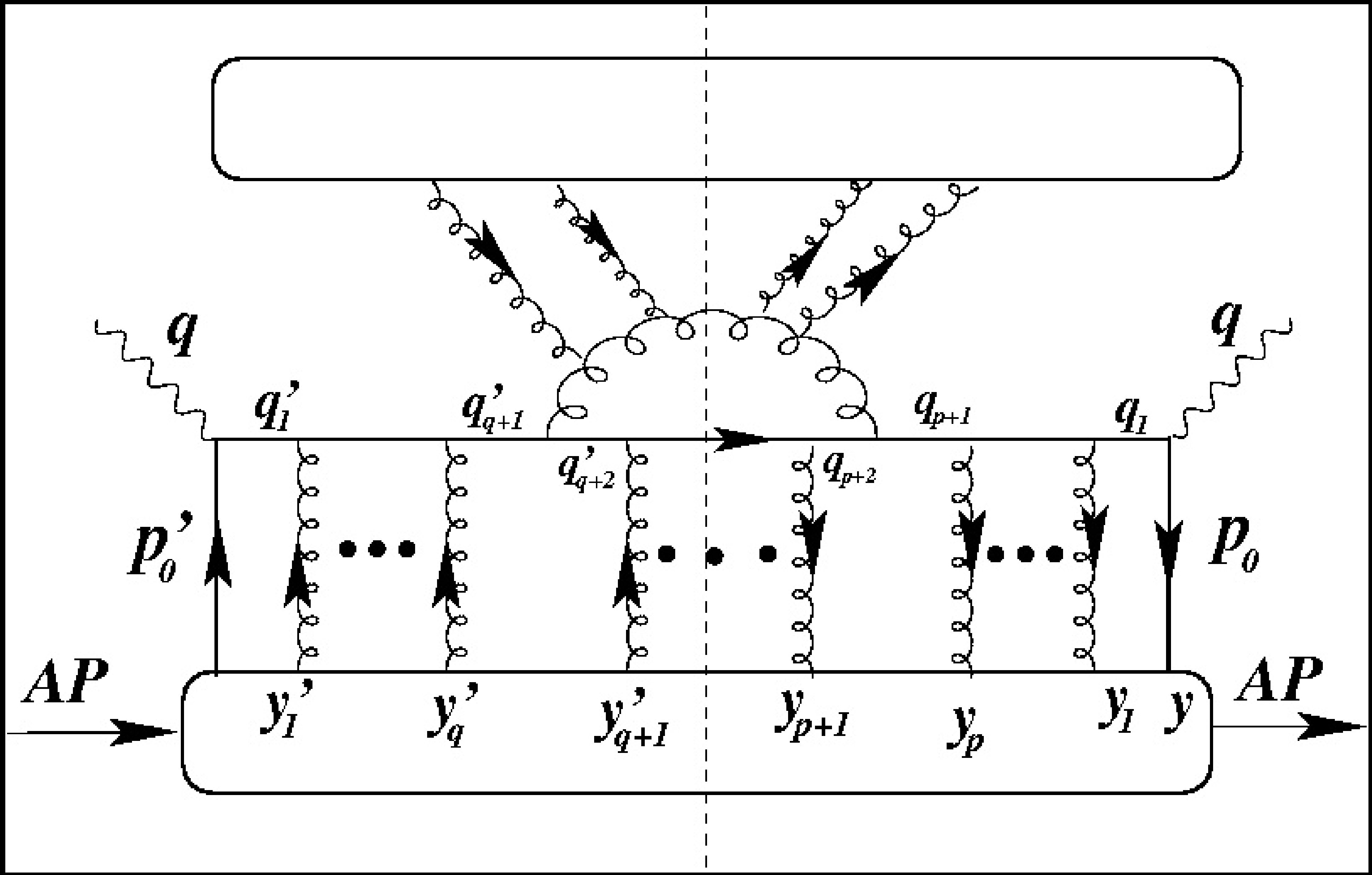


$$\langle p_\perp^2 \rangle = 4Dt$$

$$\hat{q} = \frac{p_\perp^2}{t} = \frac{2\pi^2 \alpha_S C_R}{N_c^2 - 1} \int dt \left\langle X \left| \mathrm{Tr}\left[\mathrm{U}^\dagger(\mathrm{t}, \mathrm{vt}; 0) \mathrm{t}^{\mathrm{a}} \mathrm{F}^{\mathrm{a}\mu\rho} \mathrm{v}_\rho \mathrm{U}(\mathrm{t}, \mathrm{vt}; 0) \mathrm{t}^{\mathrm{b}} \mathrm{F}^{\mathrm{b}\,\sigma}_{\ \mu}(0) \mathrm{v}_\sigma \right] \right| X \right\rangle$$

Michael Benzke et al.,

The single gluon emission kernel

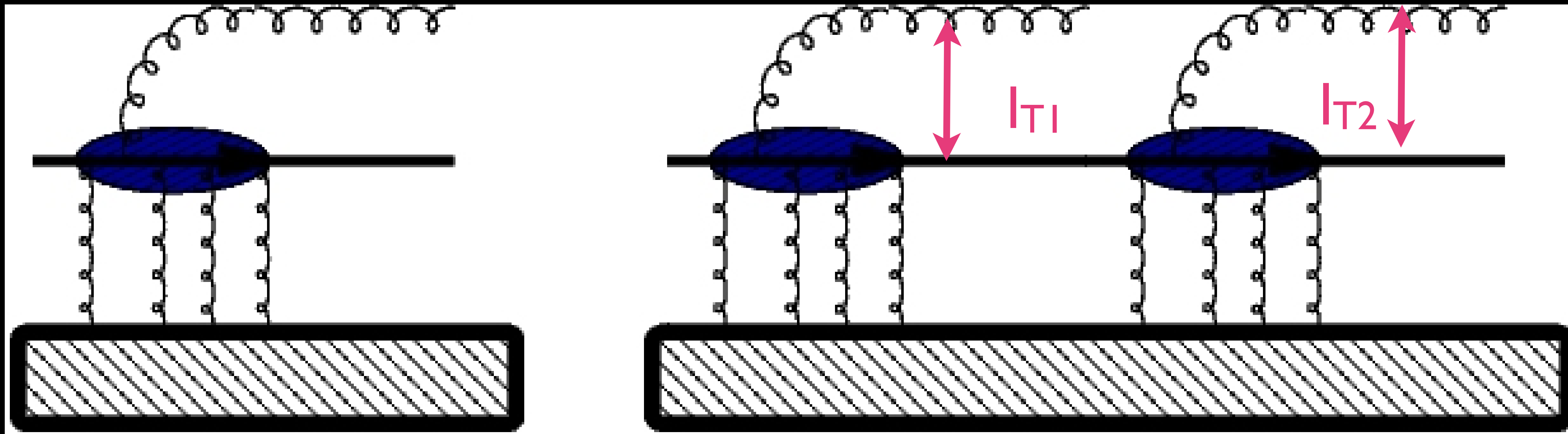


Calculate 1 gluon emission with quark & gluon N-scattering with transverse broadening and elastic loss built in

Solved analytically, in large Q^2 limit.

A. M. Phys. Rev. D 85, 014023 (2012)

Need to repeat the kernel



What is the relation between subsequent radiations ?

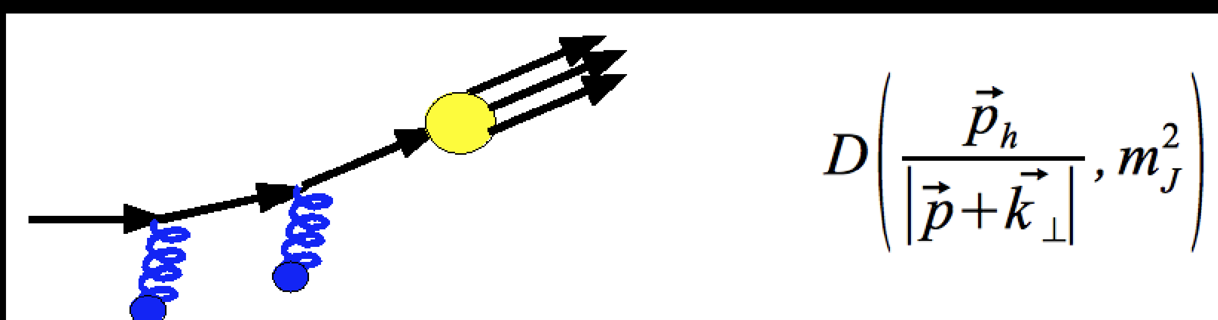
In the large Q^2 we can argue that there should be ordering of l_T.

$$if \;\; \hat{q}L \quad < \quad Q^2$$

$$\text{then} \qquad \frac{dQ^2}{Q^2}\left[1 + c_1 \frac{\hat{q}L}{Q^2}\right] \leq \frac{dQ^2}{Q^2}[1 + c_1]$$

Validity at high resolution,
transport coefficients for near on-shell partons

$$p_z^2 \simeq E^2 - p_\perp^2 \qquad\qquad p^+ \simeq p_\perp^2/2p^-$$



$$\hat{q} = \frac{\langle p_\perp^2 \rangle_L}{L}$$

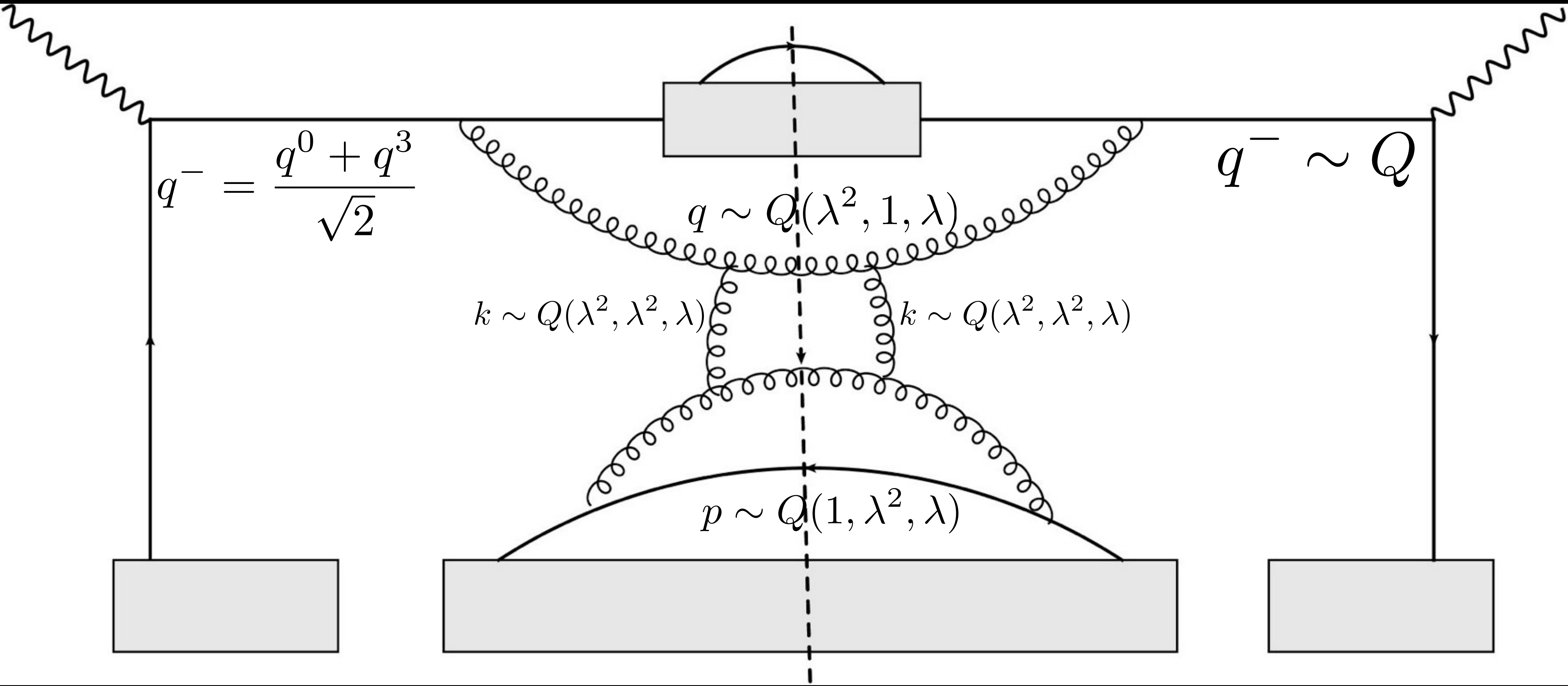
Transverse momentum diffusion rate

Notion of transport coefficient valid in the regime of

$\mu >> \Lambda_{QCD}$

A hierarchy of scales: $Q >> \mu >> \Lambda_{QCD}$

A factorized picture



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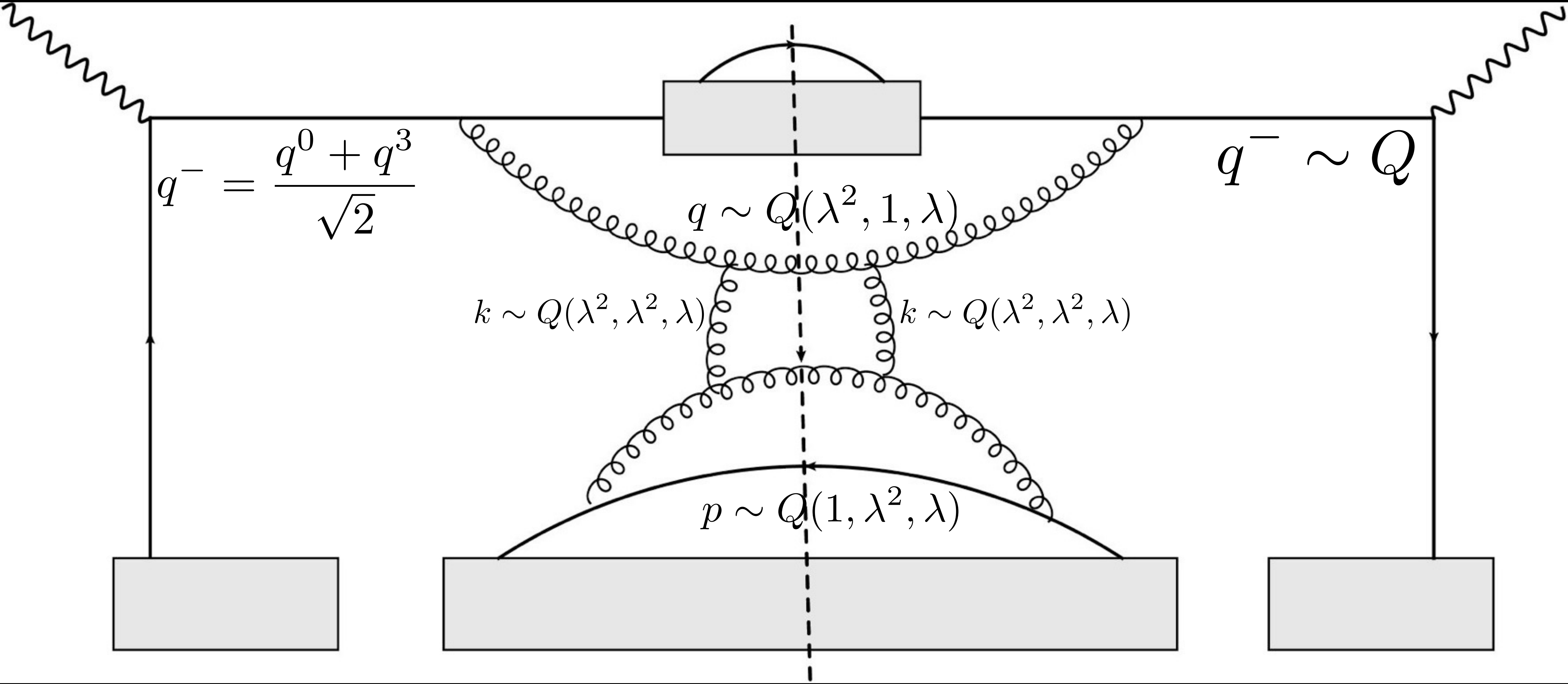
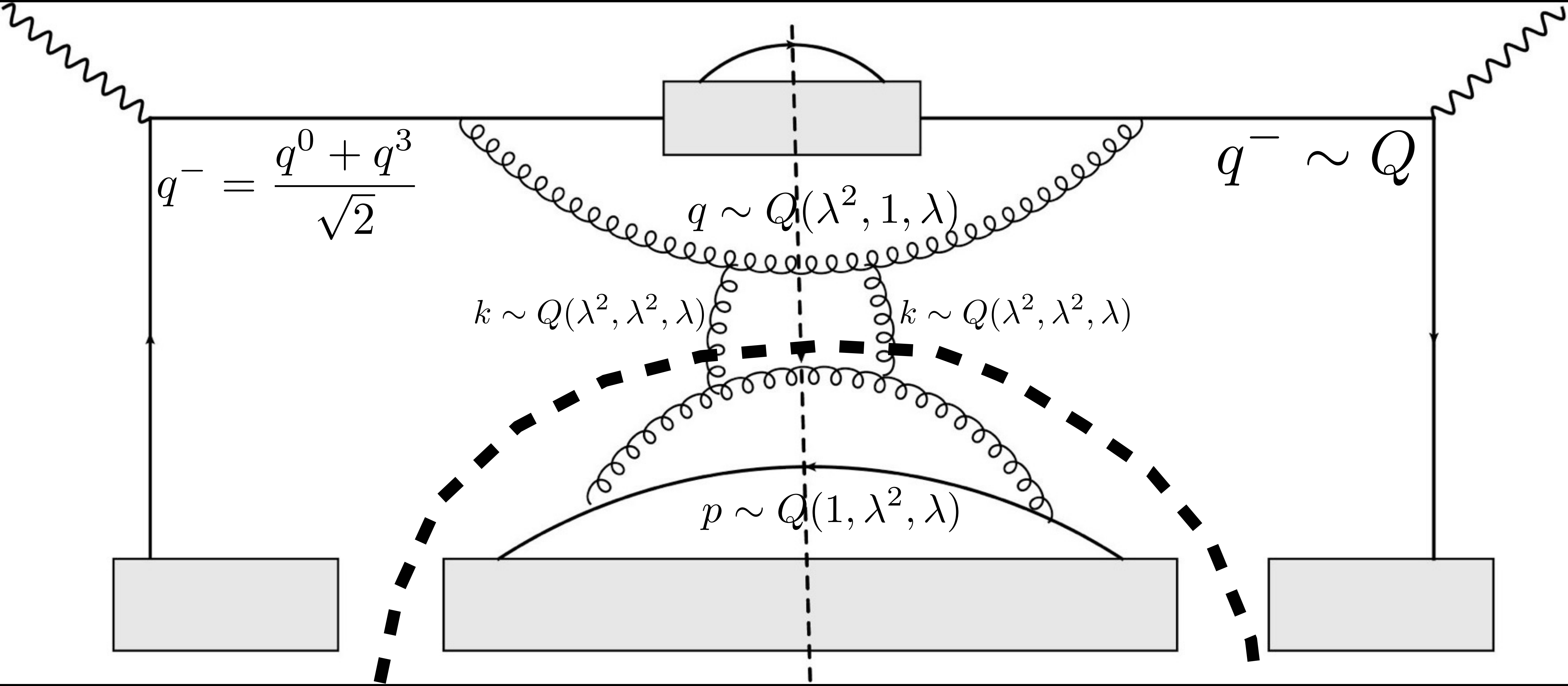


Q is the hard scale of the jet ~ E

$Q\lambda$ is a semi-hard scale ~ $(ET)^{1/2}, \lambda \longrightarrow 0$

$\hat{q}$ contains all dynamics below $Q\lambda$

A factorized picture



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$Q\lambda$ is a semi-hard scale ~ $(ET)^{1/2}, \lambda \longrightarrow 0$

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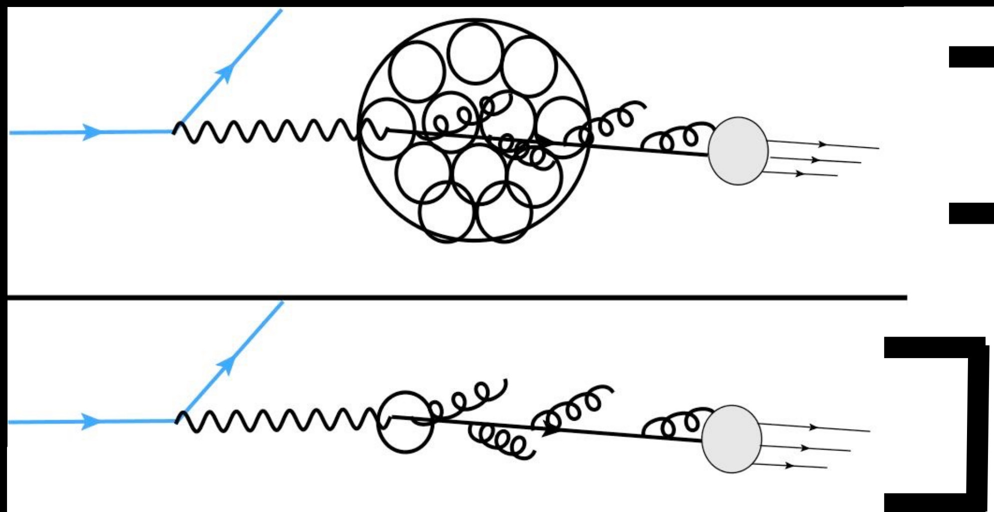
Can explain suppressed yield of hadrons in DIS



$$= \frac{N_A^h}{A \times N_p^h}$$

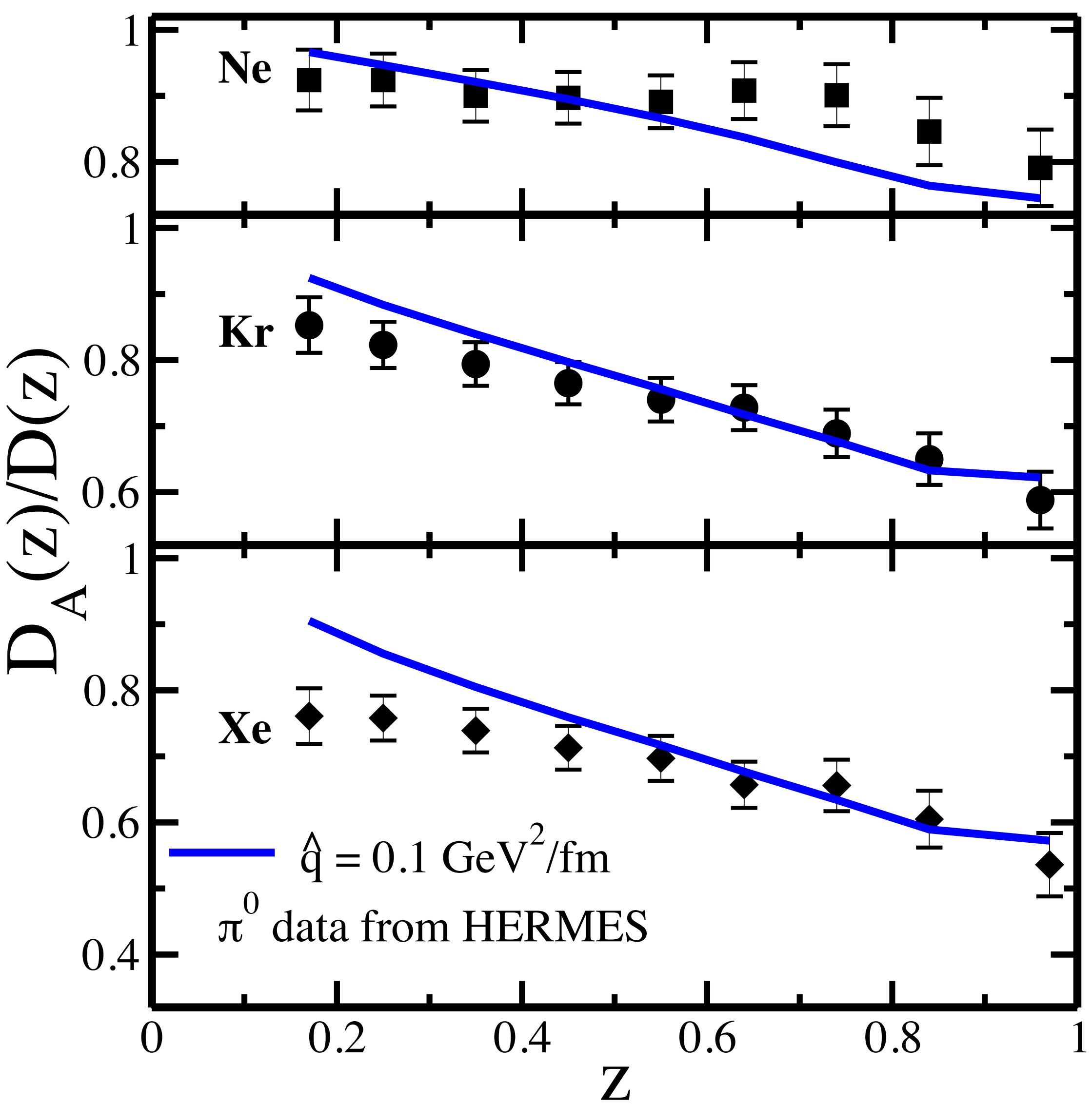
Data from HERMES at DESY

Three different nuclei

one $\hat{q} = 0.1\text{GeV}^2/\text{fm}$

Fit one data point in Ne
everything else is prediction

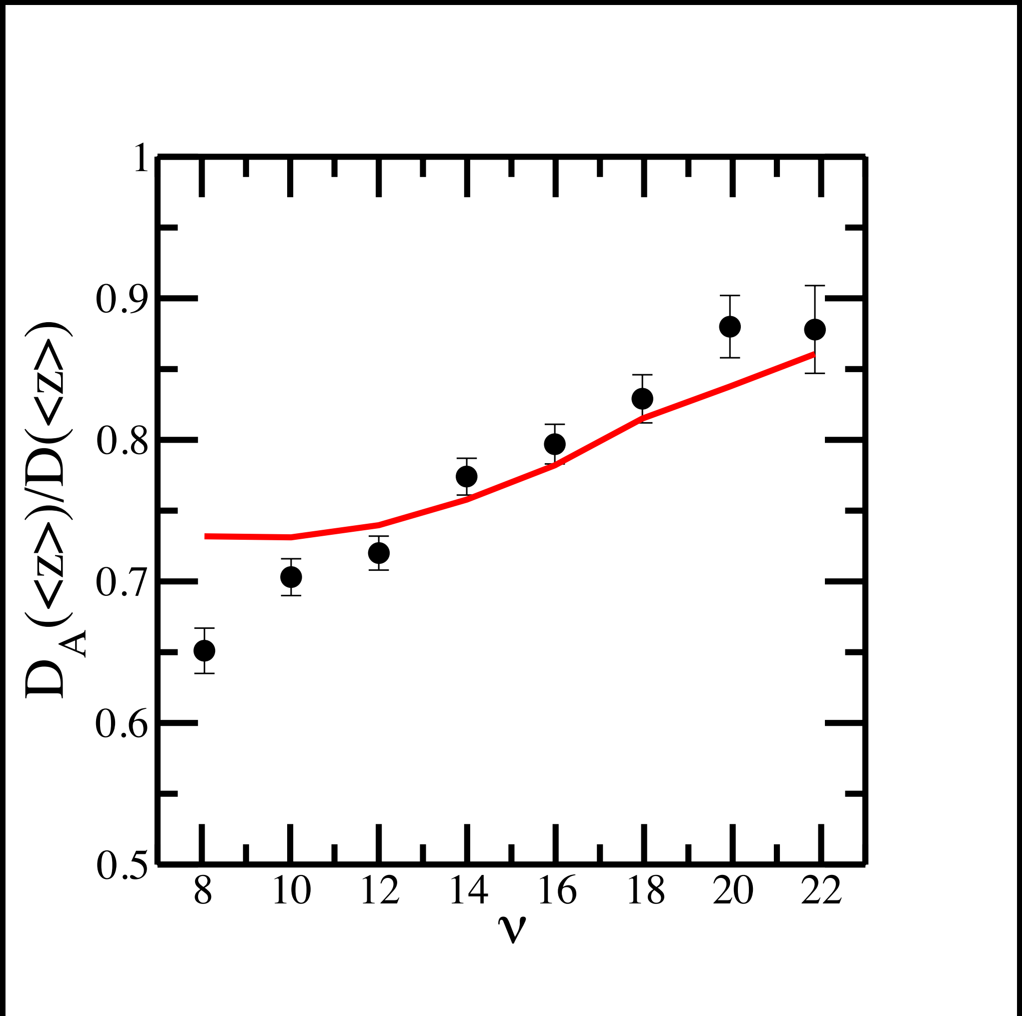
$Q^2 = 3\text{GeV}^2$, ν = 16-20 GeV

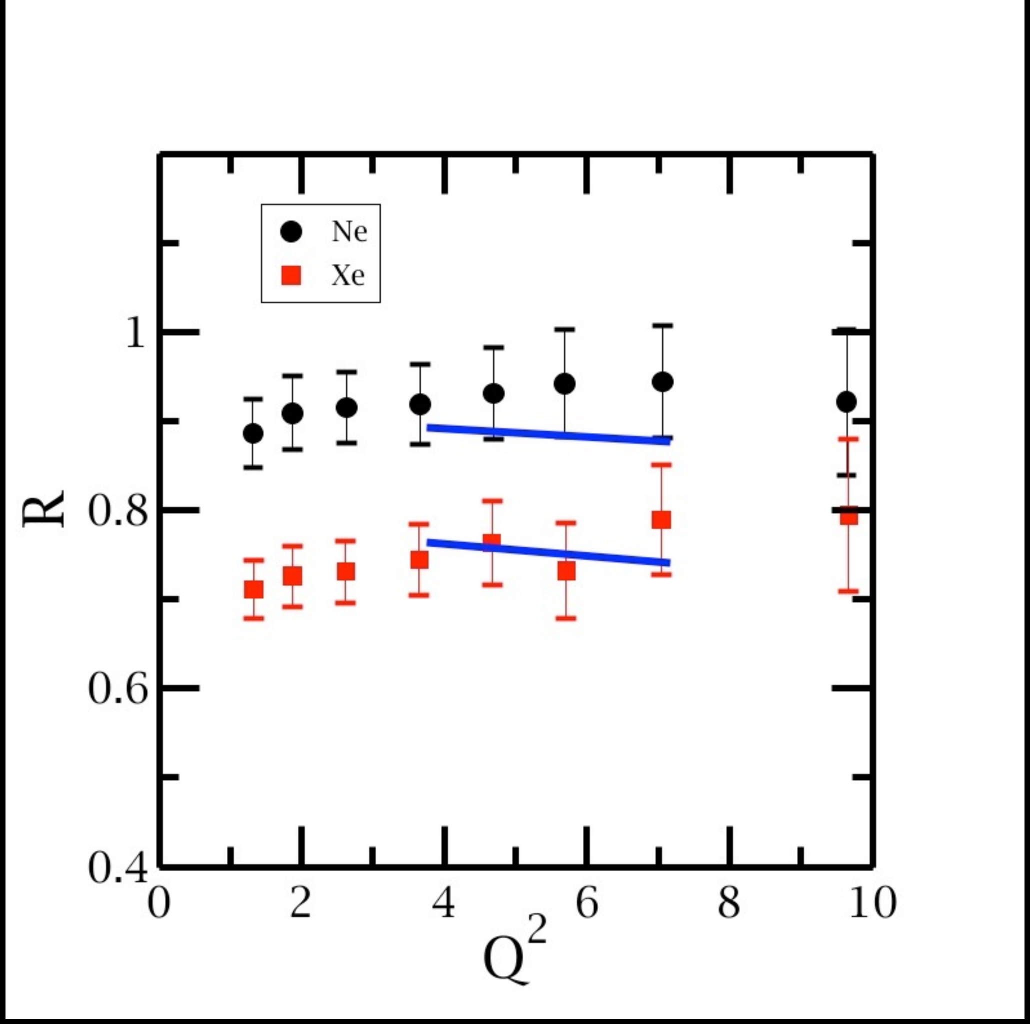


$z = E_h/E_\gamma$

A. Majumder 2009

The ν and Q^2 dependence

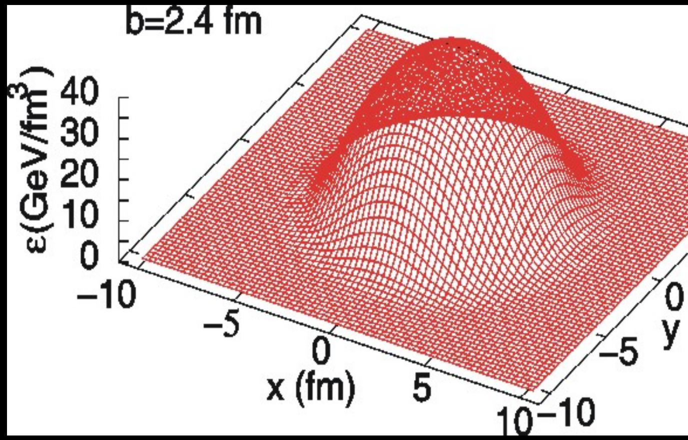




Now factorize the final state parton and transplant in a heavy-ion collision

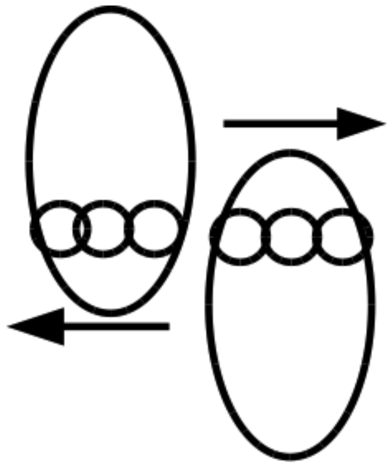
In all calculations presented bulk medium described by viscous fluid dynamics

Medium evolves hydro-dynamically as the jet moves through it
Fit the $\hat{q}$ for the initial T in the hydro in central coll.

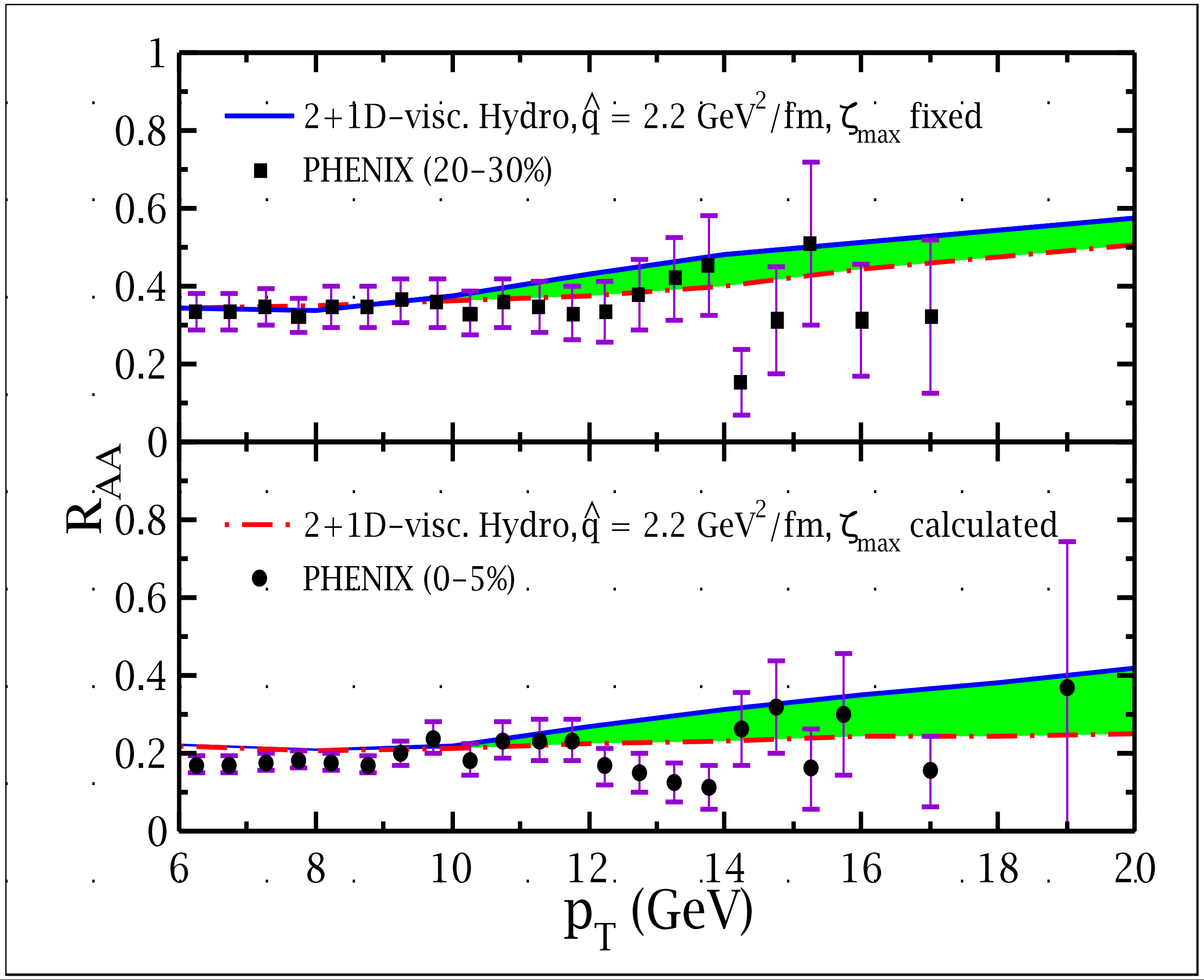


$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

$$s_0 = s(T_0)$$

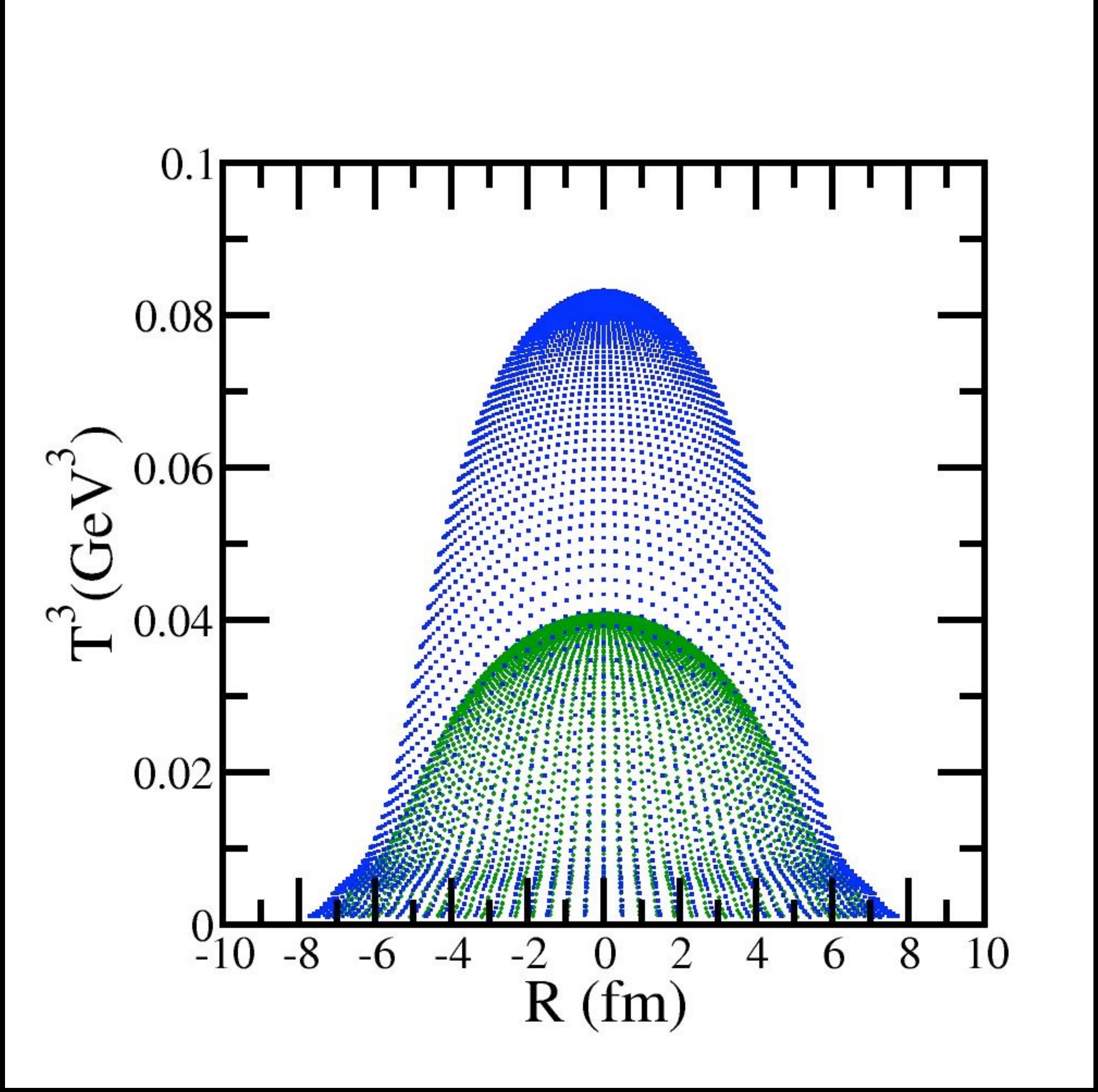


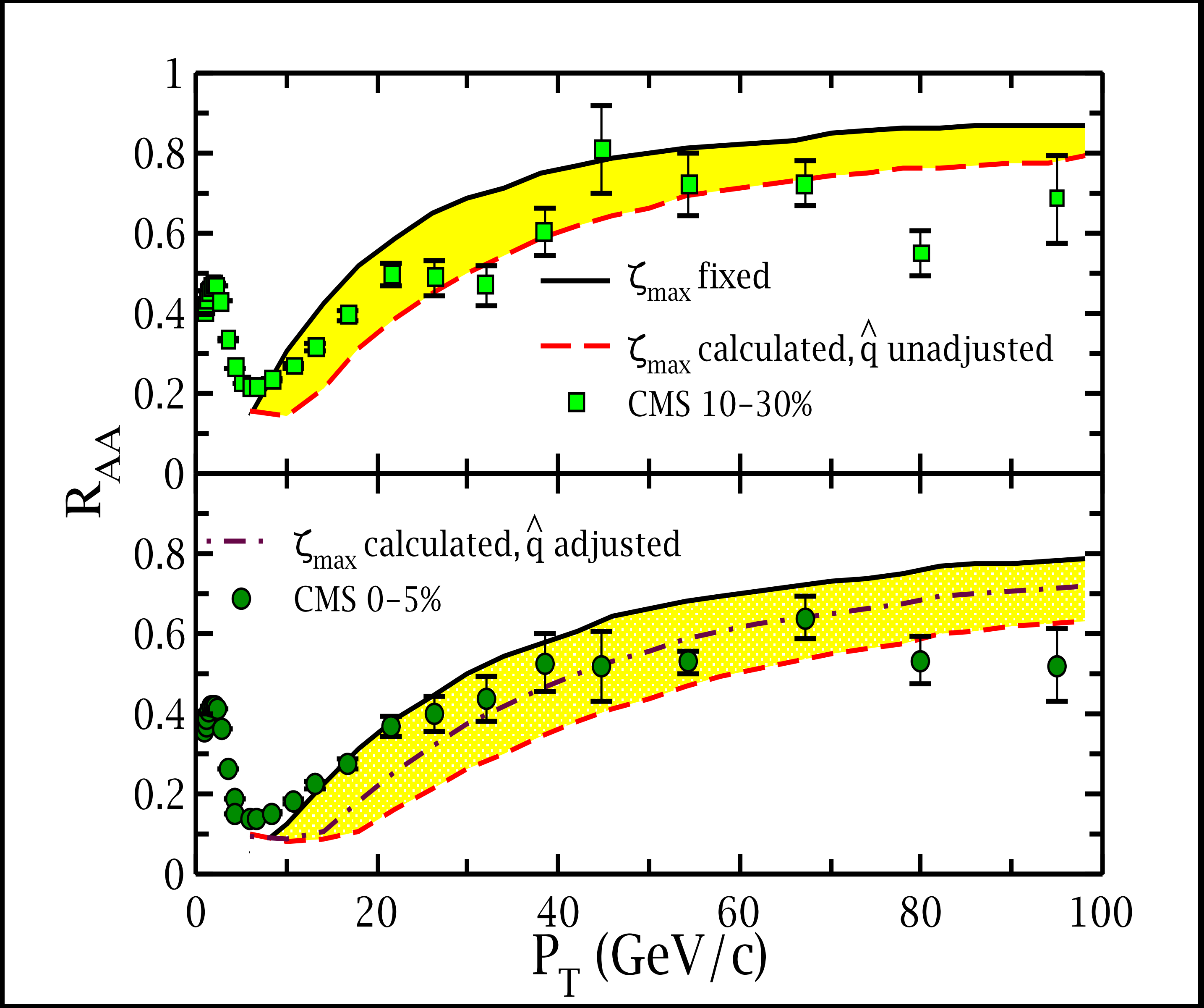
$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin} \frac{dN_{pp}}{dp_T dy}}$$



A.M. & C. Shen Phys.Rev.Lett. 109 (2012) 202301

From RHIC to LHC circa 2012

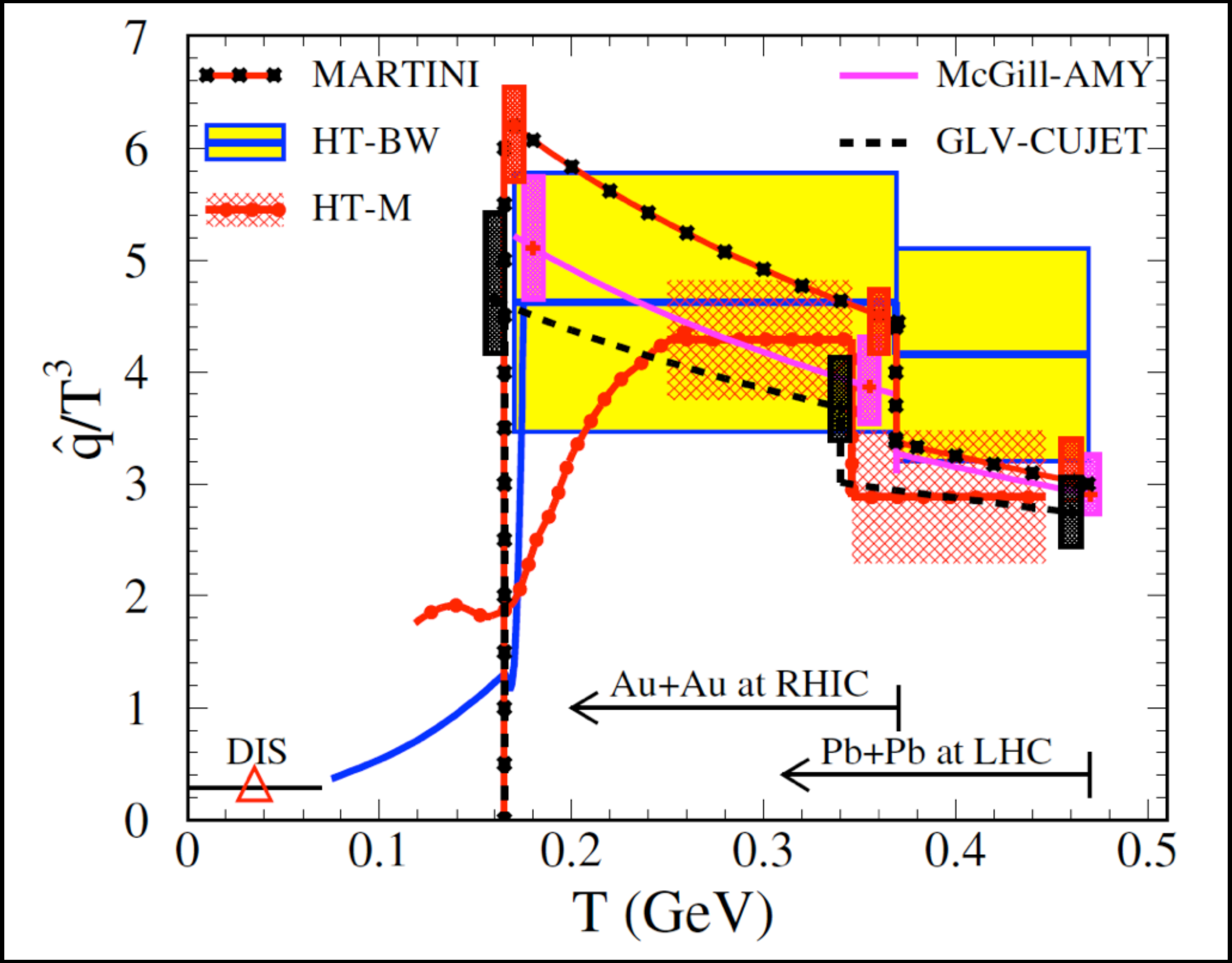




Reasonable agreement with data,
no separate normalization at LHC

Without any non-trivial x-dependence (E dependence)

Results from the JET collaboration

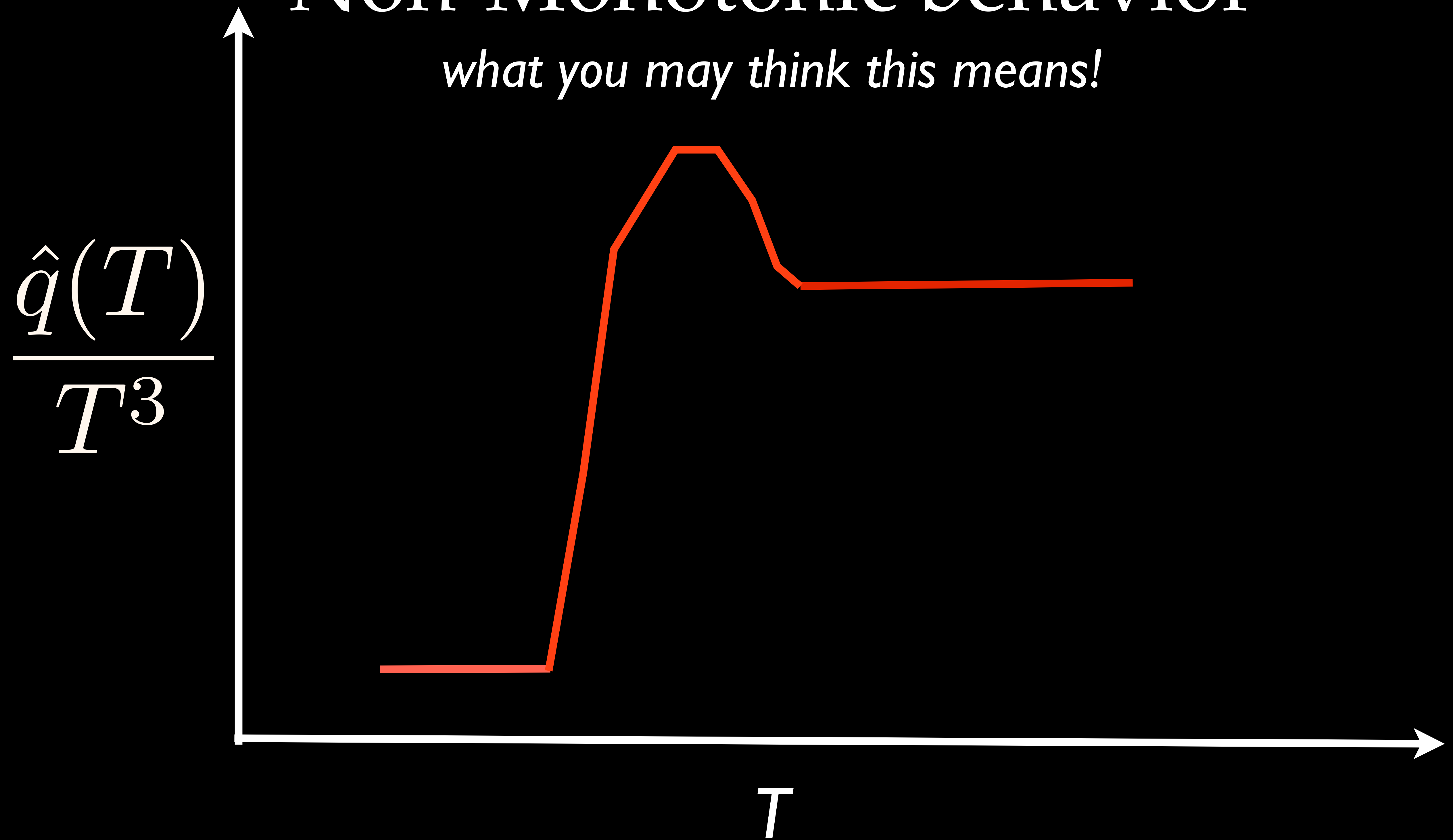


Do separate fits to the RHIC and LHC data for maximal $\hat{q}$ without assuming any kink in the $\hat{q}$ vs T^3 curve

K. Burke et al. Phys.Rev. C90 (2014) no.1, 014909

Non-Monotonic behavior

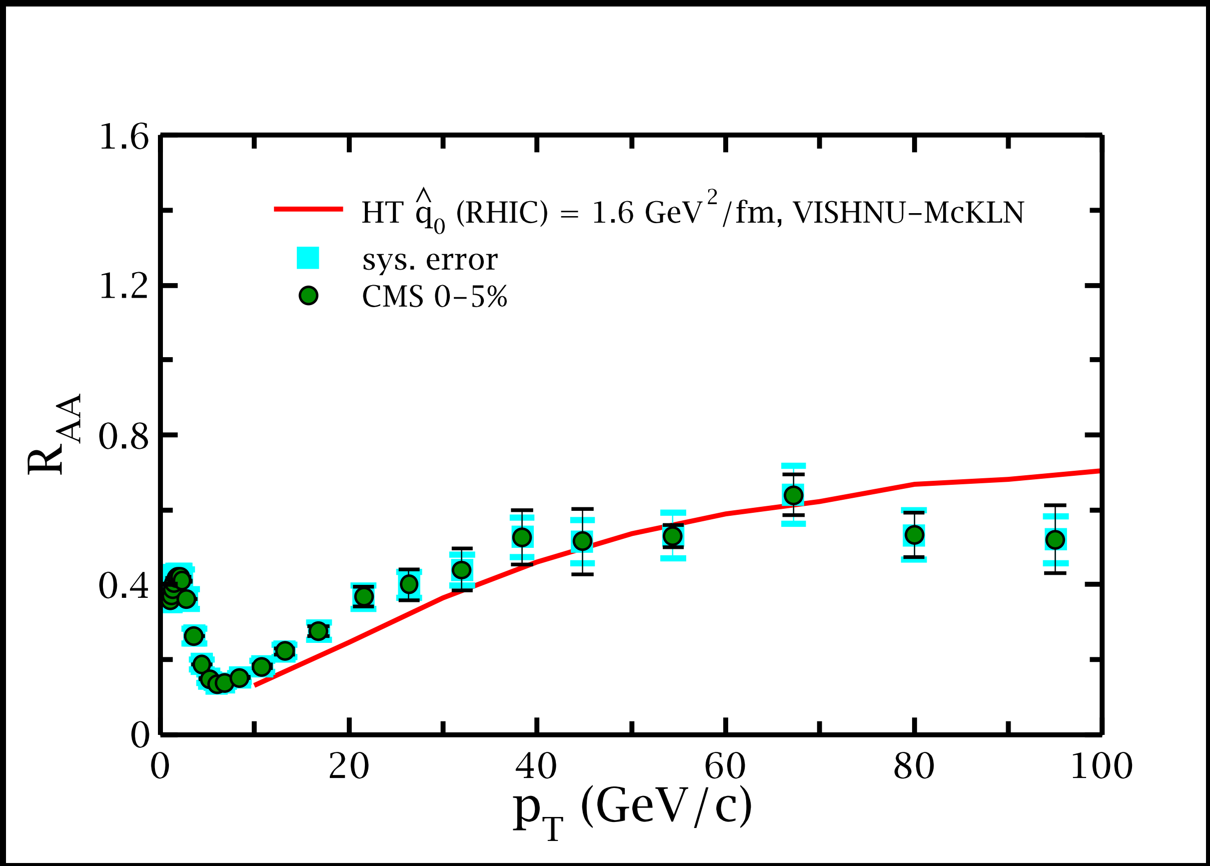
what you may think this means!

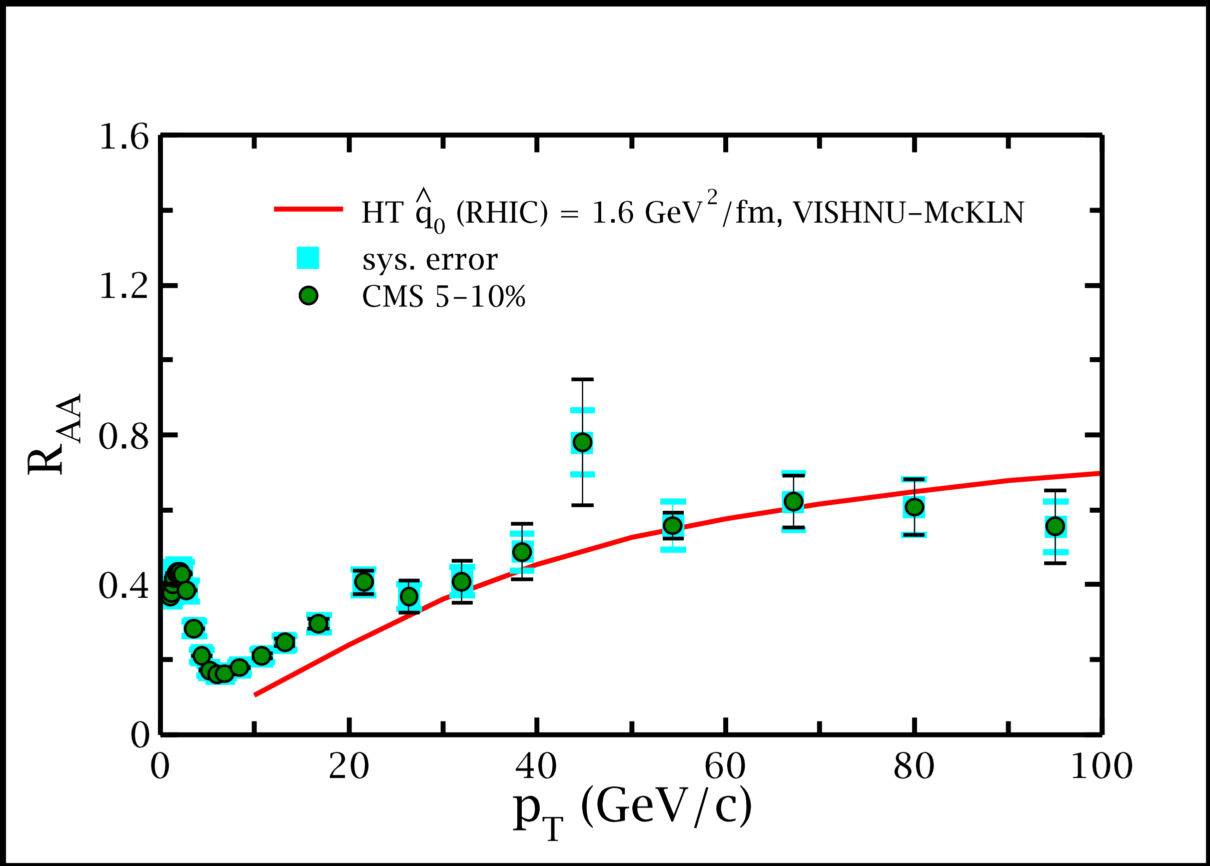


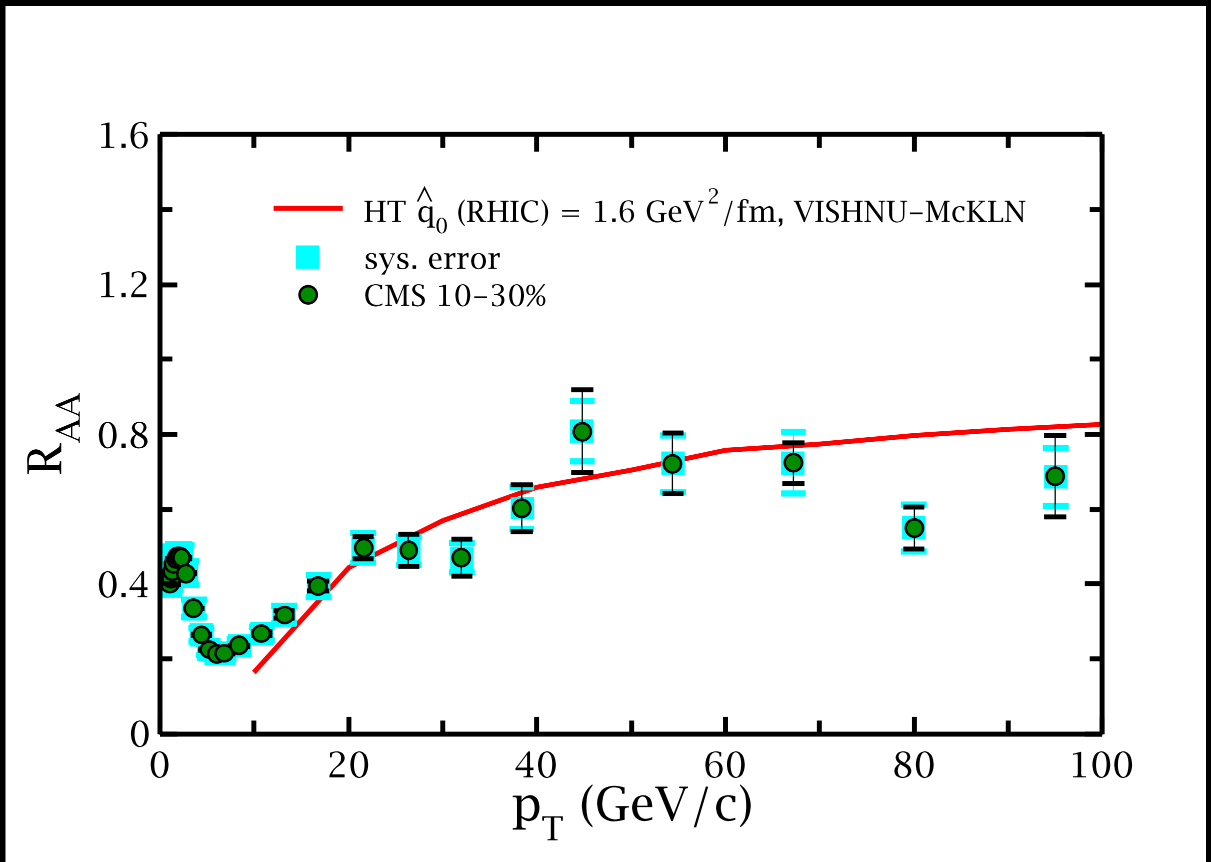
If this is true, must effect the centrality dependence of R_{AA}, v_2, and its centrality dependence at a given collision energy

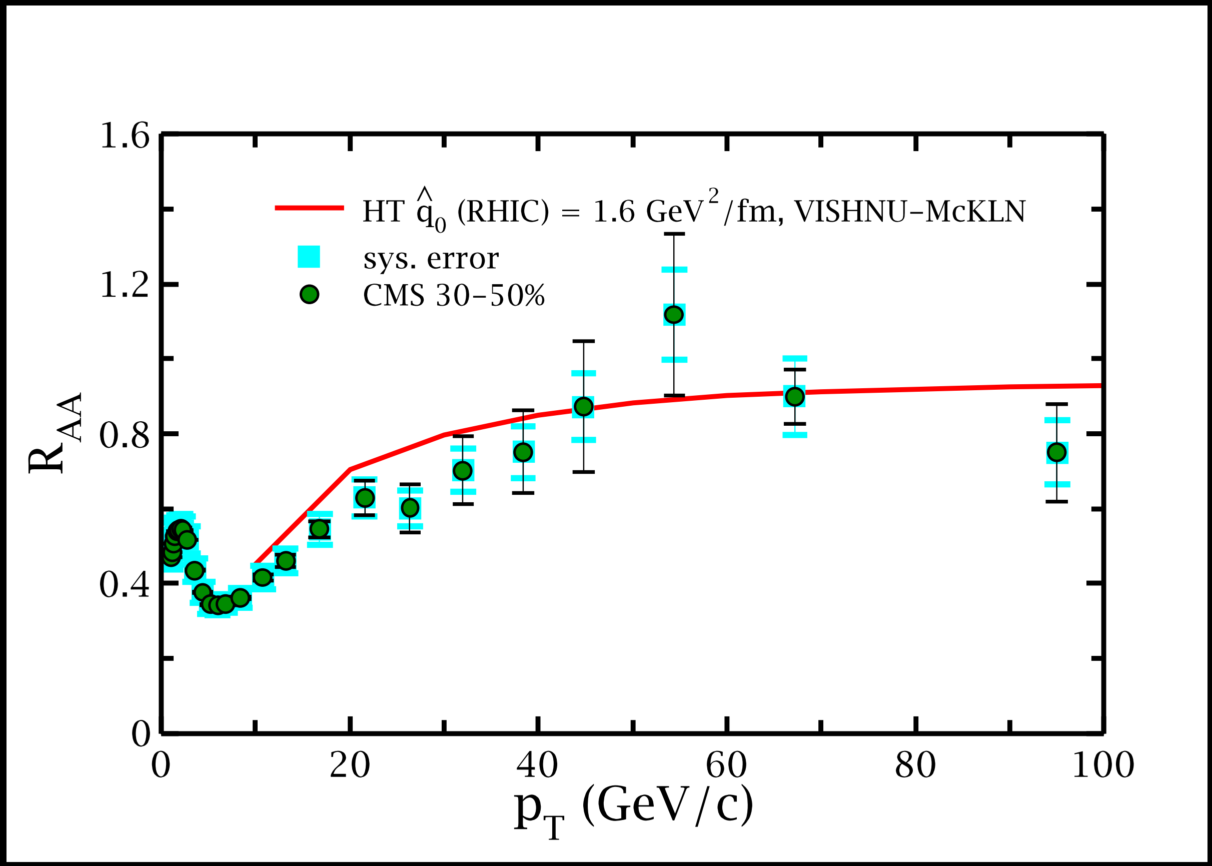
J. Xu, J.-F. Liao, M. Gyulassy JHEP 1602 (2016) 169

LHC R_{AA} without a bump in $\hat{q}/T^3$

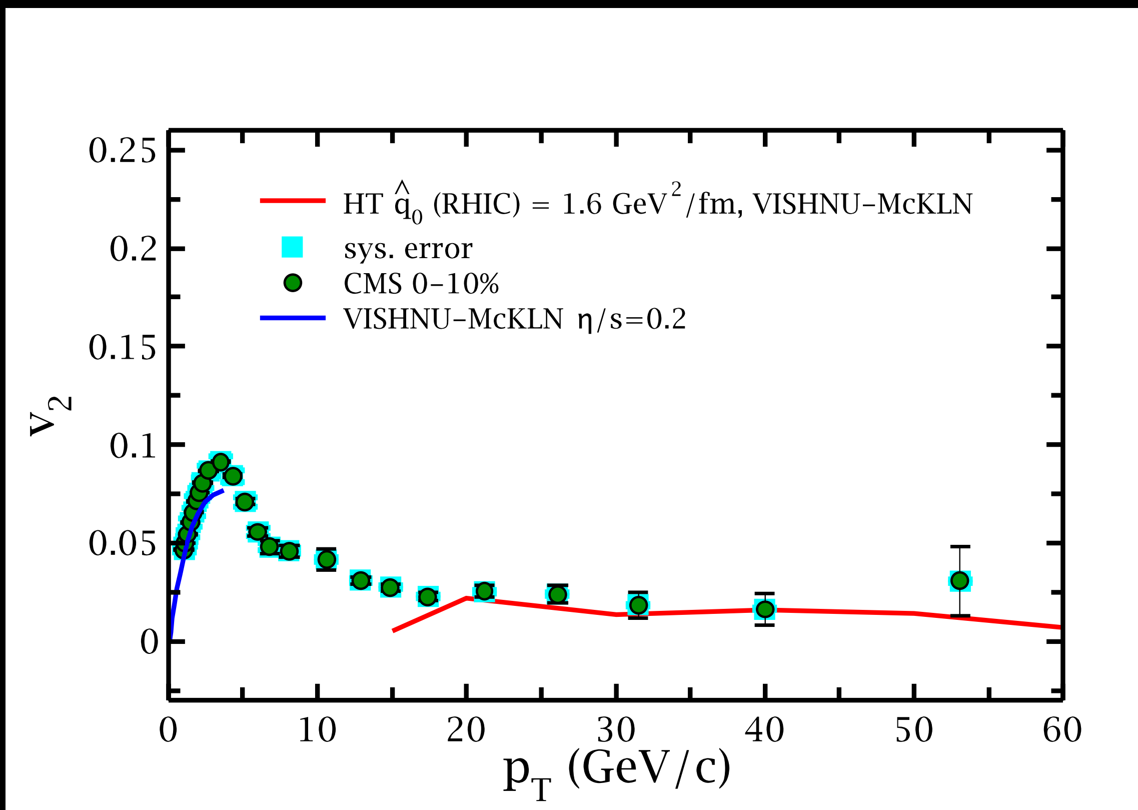


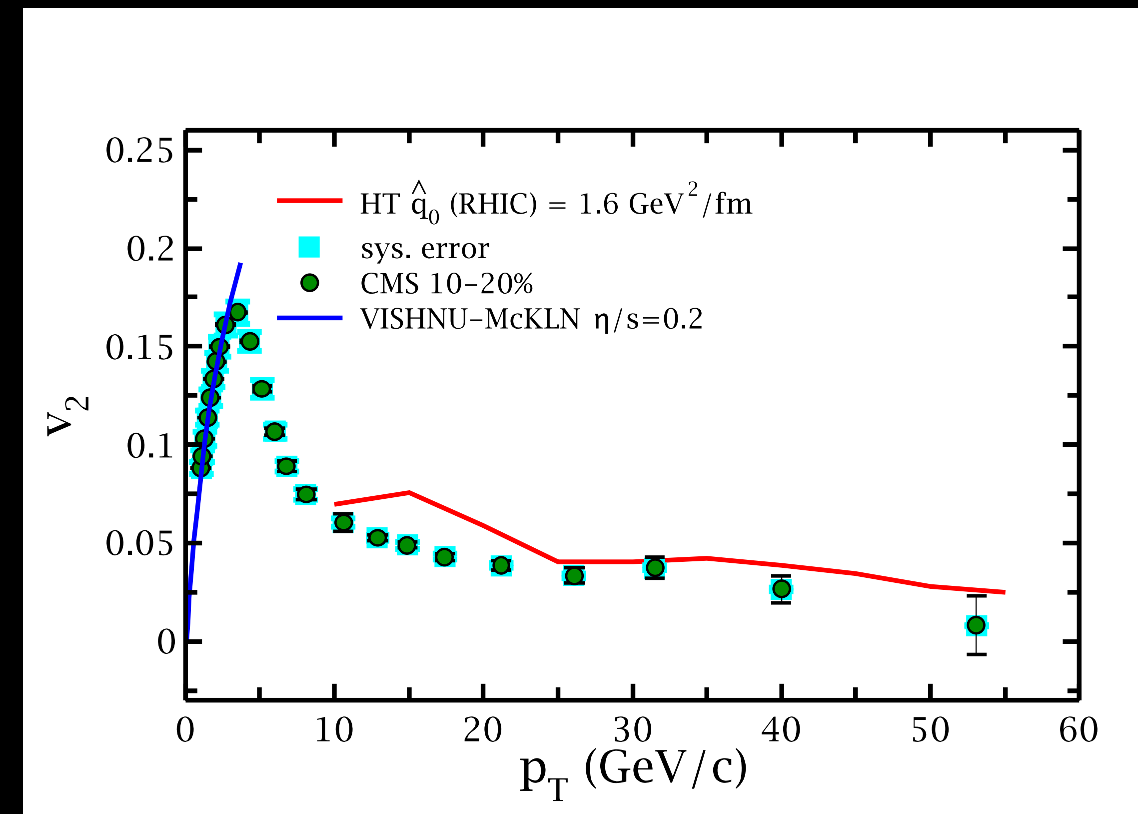


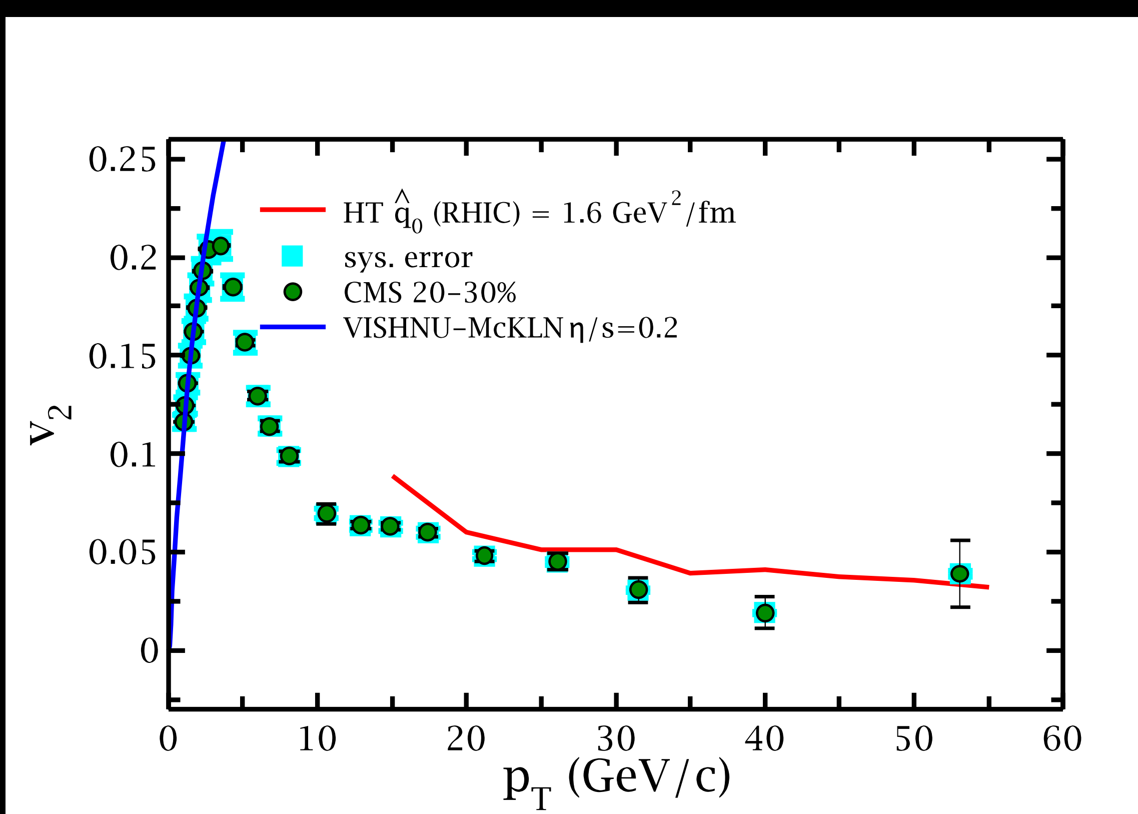


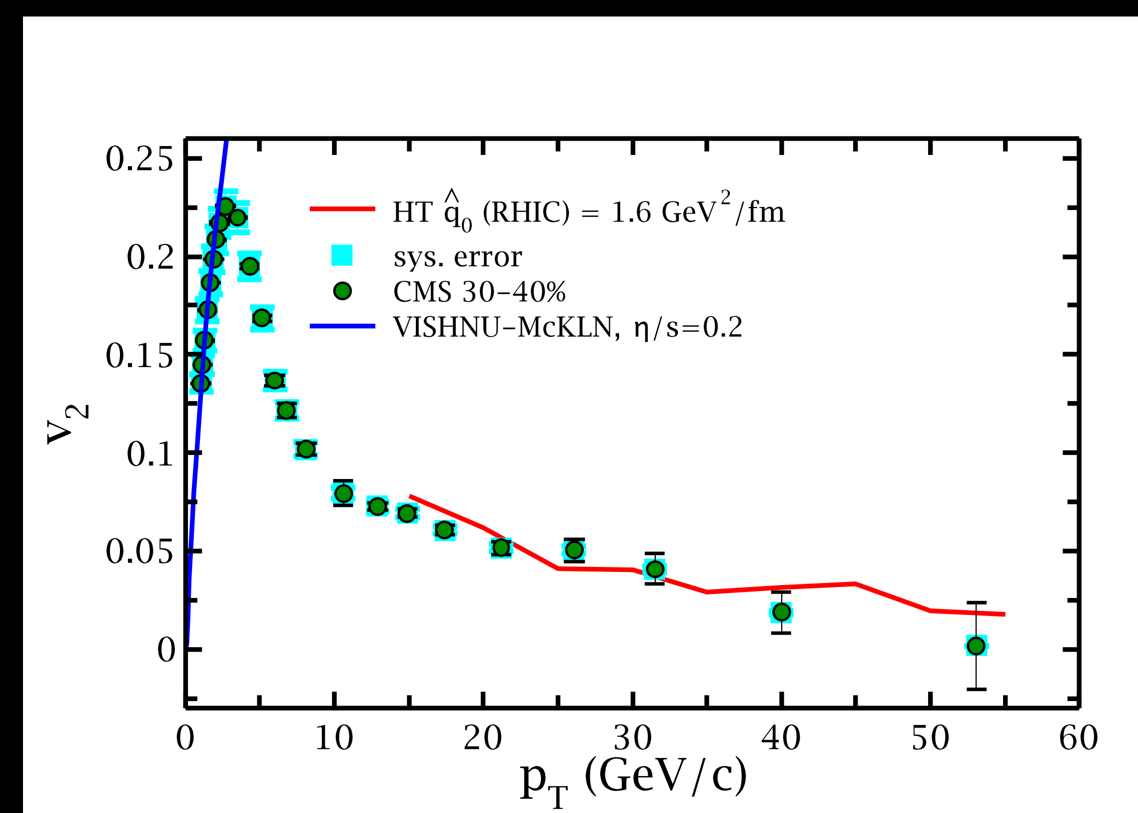


v_2 at LHC without a bump in $\hat{q}/T^3$

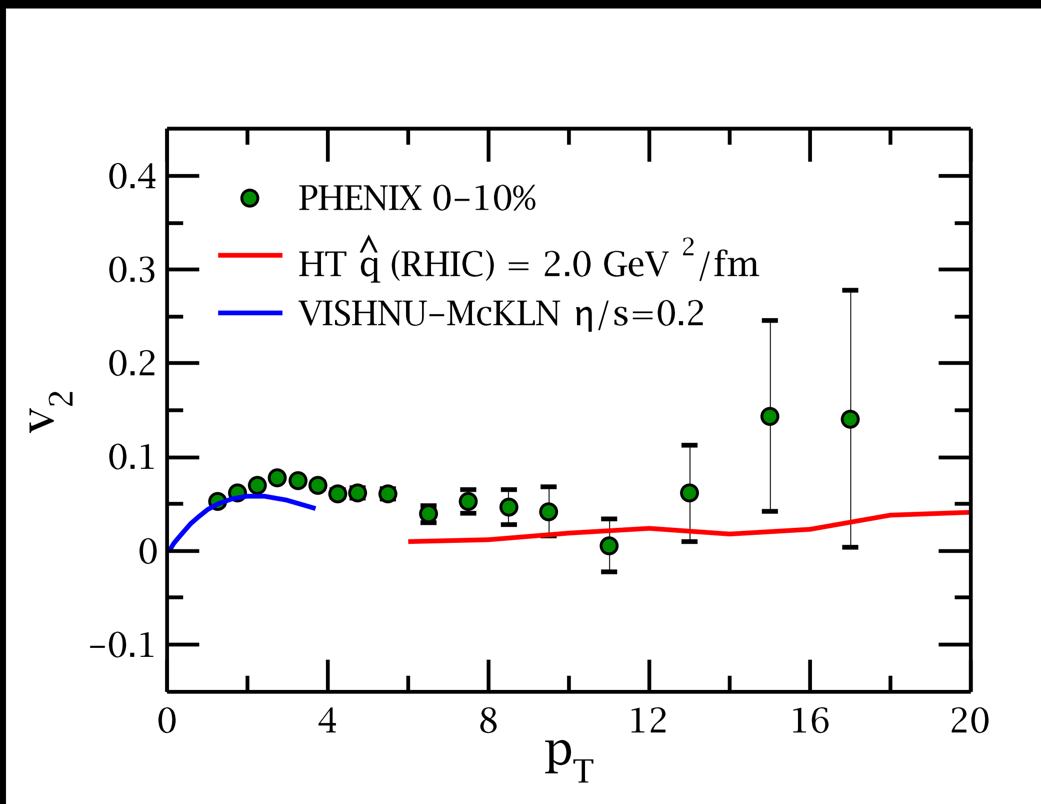


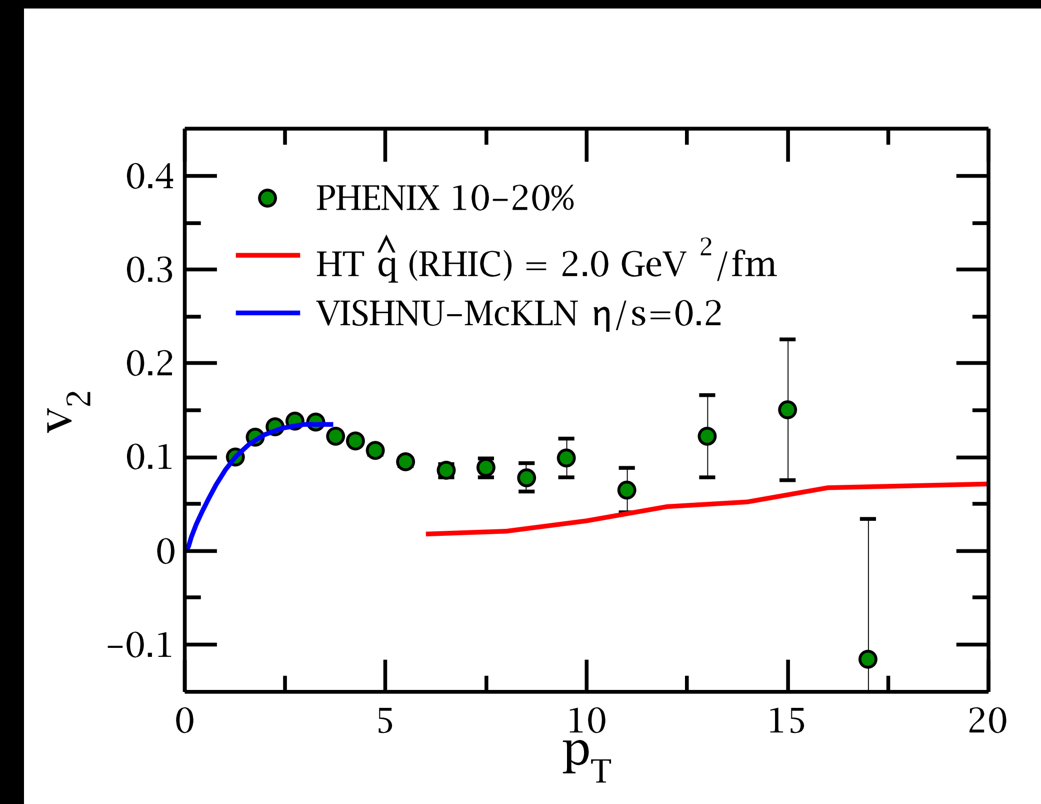


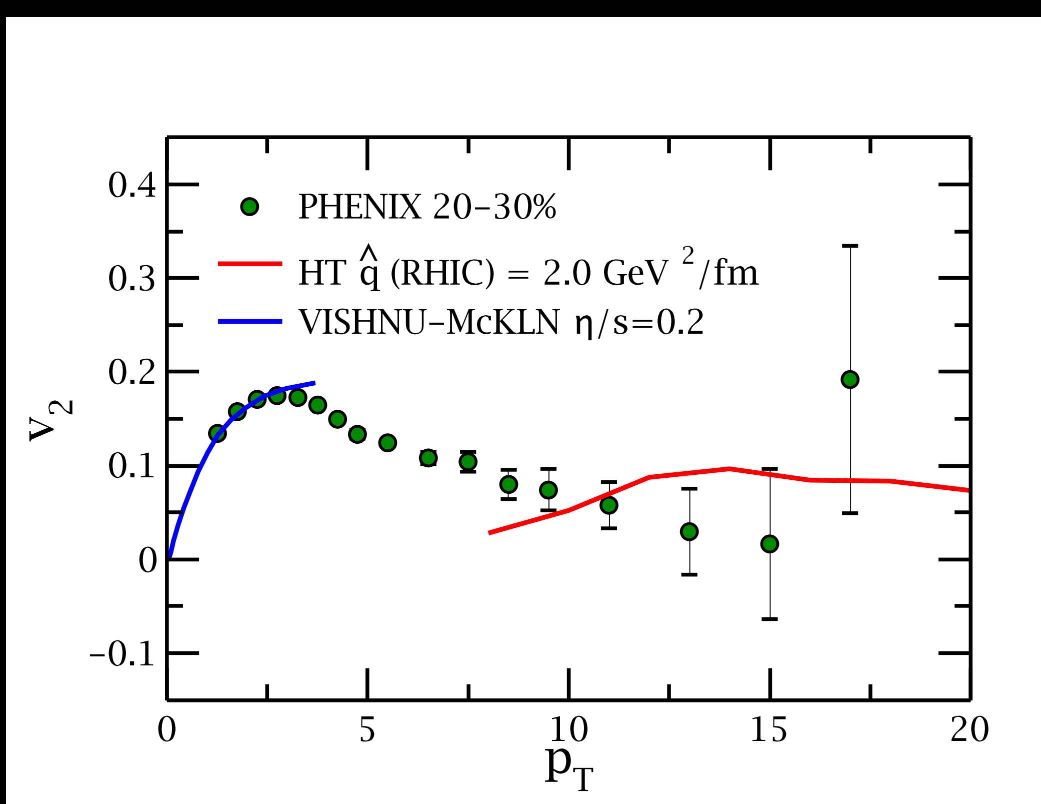


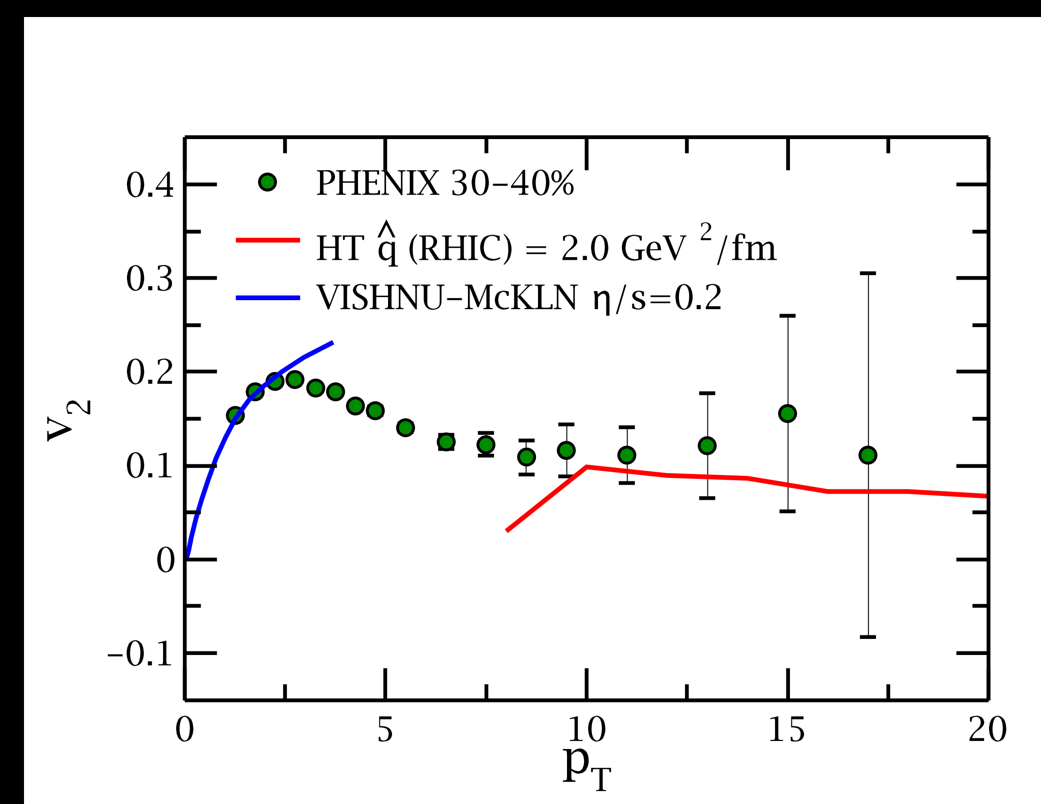


v_2 at RHIC without a bump in $\hat{q}/T^3$

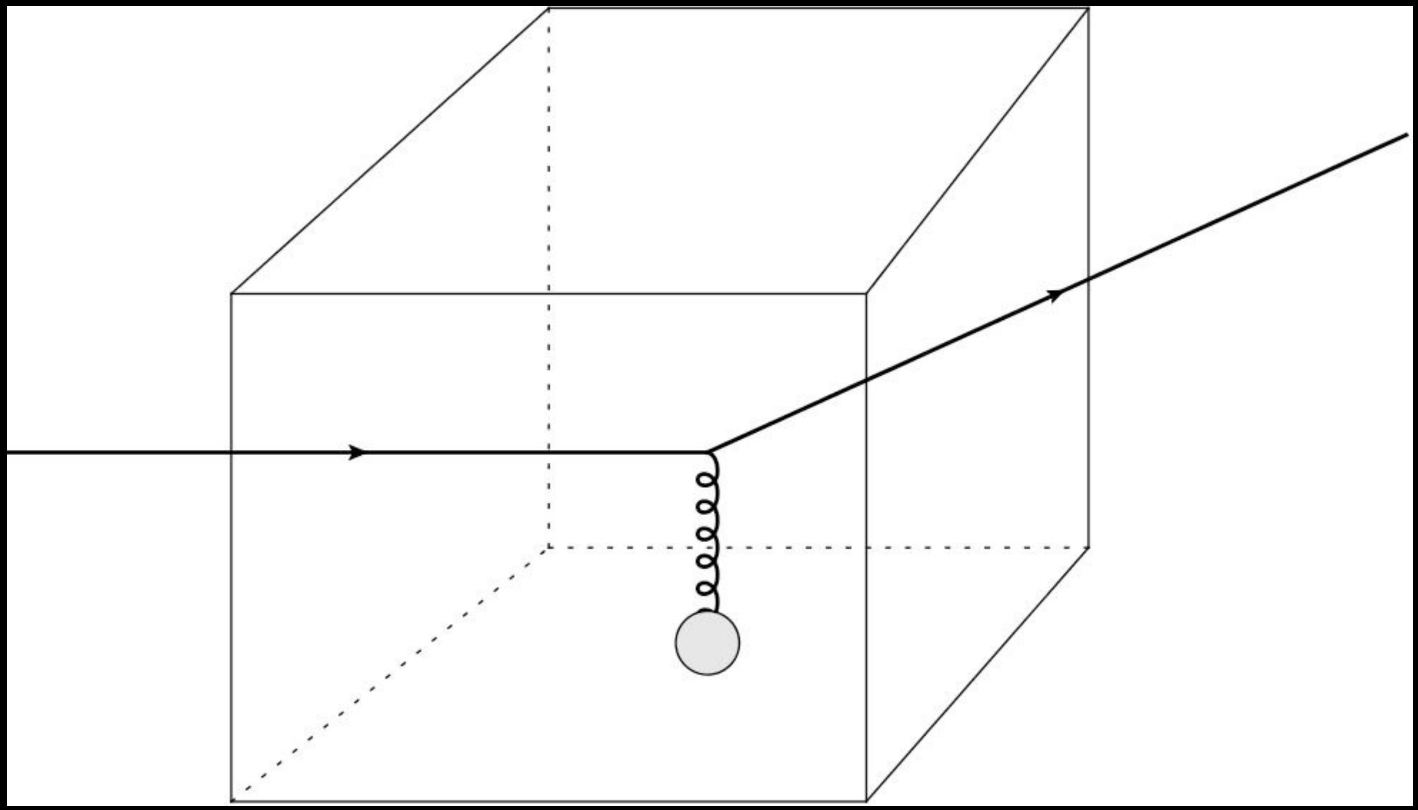








Calculating $\hat{q}$ with more care



$$
\begin{aligned}
W(k) \quad &= \quad \frac{g^2}{2N_c}\langle q^-; M| \int d^4x d^4y \bar{\psi}(y) \not{A}(y)\psi(y) \\
&\times \quad |q^- + k_\perp; X\rangle\langle q^- + k_\perp; X| \\
&\times \quad \bar{\psi}(x) \not{A}(x)\psi(x)|q^-; M\rangle
\end{aligned}
$$

in terms of W, we get $\hat{q} = \sum_k k_\perp^2 \frac{W(k)}{t},$

Final state is close to ``on-shell''

$$\delta[(q+k)^2] \simeq \frac{1}{2q^-}\delta\left(k^+ - \frac{k_\perp^2}{2q^-}\right).$$

Also we are calculating in a finite temperature heat bath

$$\hat{q} = \frac{4\pi^2\alpha_s}{N_c}\int \frac{dy^- d^2y_\perp}{(2\pi)^3} d^2k_\perp e^{-i\frac{k_\perp^2}{2q^-}y^- + i\vec{k}_\perp\cdot\vec{y_\perp}}$$

$$\langle n|F^{+,}{}_\perp(y^-,\vec{y}_\perp)F_\perp^+(0)|n\rangle$$

$$\hat{q}(q^+,q^-)$$

$$2q^-q^+ = Q^2,\ \ \frac{k_\perp^2}{2q^-} = xP^+$$

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$$\hat{q}(q^+,q^-)$$

$$2q^-q^+ = Q^2, \;\; \frac{k_\perp^2}{2q^-} = xP^+$$

What one usually does at this point

- Take the q^- to be infinity

$$\hat{q} \sim \int \frac{dy^- d^2 y_\perp}{(2\pi)^3} d^2 k_\perp e^{i\vec{k}_\perp \cdot \vec{y}_\perp} \langle n | F^{+,}{}_\perp (y^-, \vec{y}_\perp) F^+_\perp (0) | n \rangle$$

$$= \int \frac{dy^-}{2\pi} \langle n | F^{+,}{}_\perp (y^-) F^+_\perp (0) | n \rangle$$

This makes $\hat{q}$ into a one dimensional quantity
an assumption of small x or high E.

e.g. in A-DIS $x = (\Lambda_{QCD}{}^2 - \mu^2)/2M\nu = 1 \times 10^{-3} - 2 \times 10^{-2}$

$\hat{q}$ at vanishing x has been taken to NLO

Z. Kang, E. Wang, X.-N. Wang, H. Xing, PRL 112 (2014) 102001

T. Liou, A. Mueller, B. Wu, Nucl.Phys. A916 (2013) 102-125

J. Blaizot, Y. Mehtar-tani, arXiv:1403.2323 [hep-ph]

E. Iancu, arXiv:1403.1996 [hep-ph]

None of these NLO corrections have been tested
in jet based phenomenology.

What is x for a QGP

- Bjorken x in DIS on a proton $$x_B = \frac{Q^2}{2p \cdot Q}$$

- In rest frame of proton $$x_B = \frac{Q^2}{2E \cdot M} = \frac{\eta}{M}$$

- In the PDF $$f(x_B) = \int \frac{dy^-}{2\pi} e^{ix_B P^+ y^-} \langle P|\bar{\psi}(y^-)\frac{\gamma^+}{2}\psi|P\rangle$$

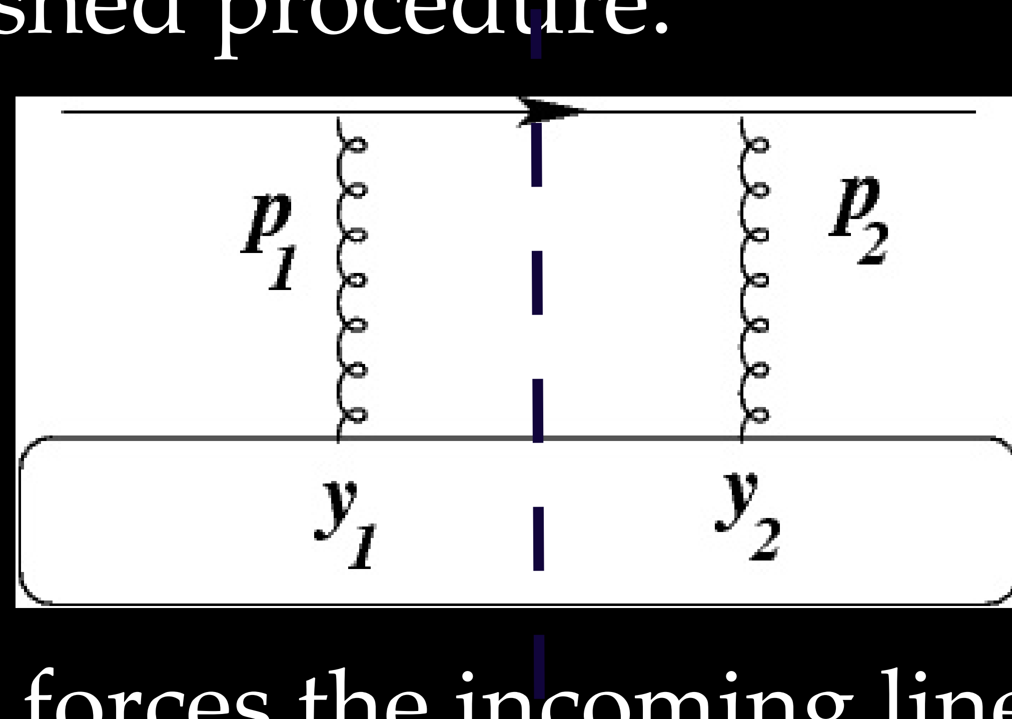
$$g(\eta) = \int \frac{dy^-}{2\pi} e^{i\eta y^-} \langle P|\bar{\psi}(y^-)\frac{\gamma^+}{2}\psi|P\rangle$$

In the rest frame of the proton, x ~ η

We can compare η values between DIS and heavy-ions

How about x or η dependence of $\hat{q}$

- The Glauber condition prevents a direct application of this established procedure.



$$\delta\left(k^+ - \frac{k_\perp^2}{2q^-}\right)$$ forces the incoming lines off-shell

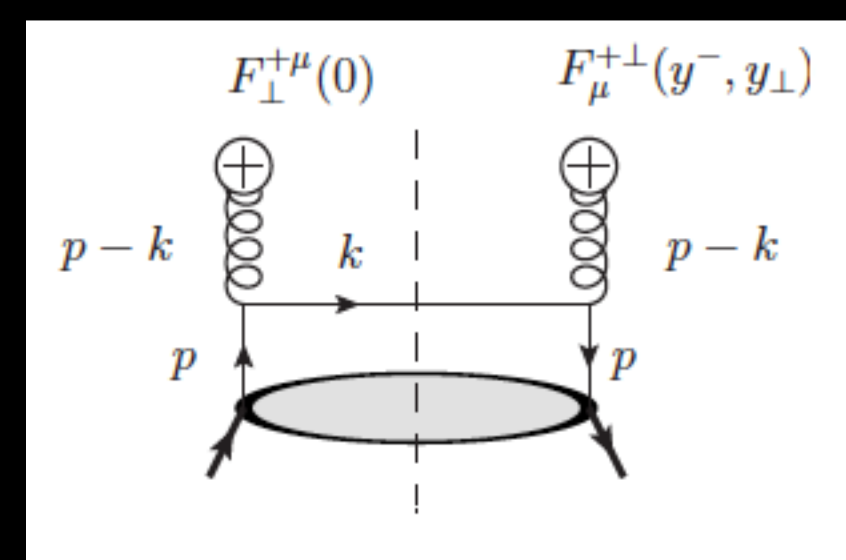
$\hat{q}$ is a 3-D object depending on x, $\underline{k}_T$

Like a TMDPDF,

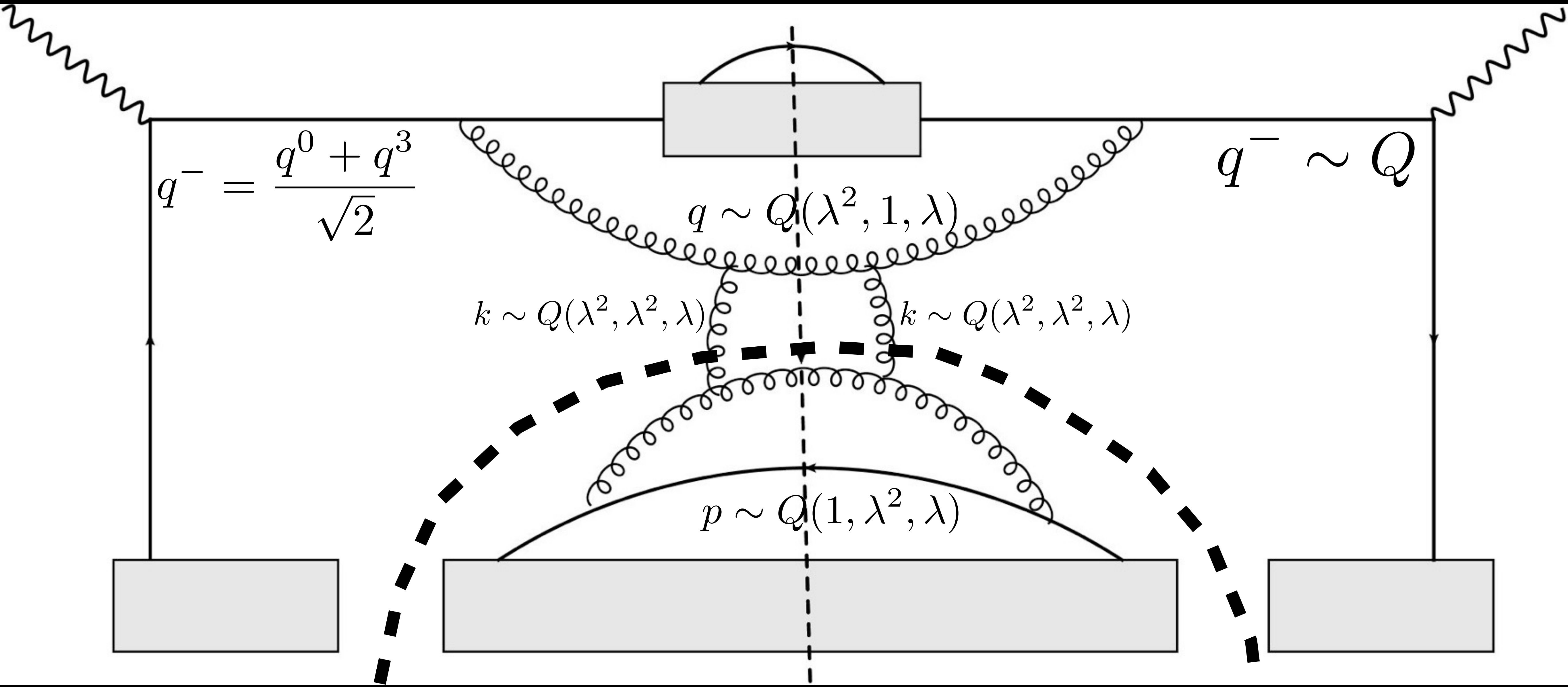
at large $\underline{k}_T$ can *refactorize* to

regular PDF X radiated gluon

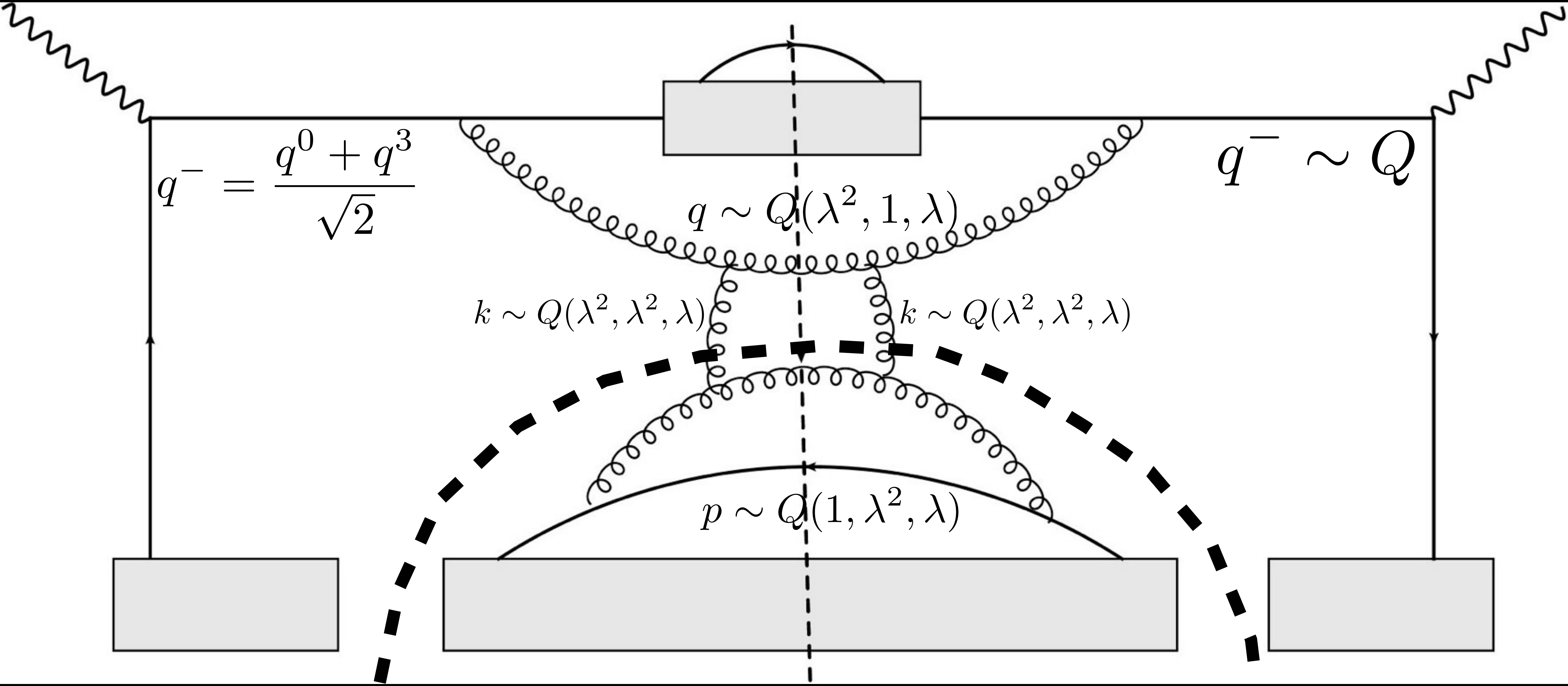
Contributions start at order α_S,



A factorized picture



A factorized picture

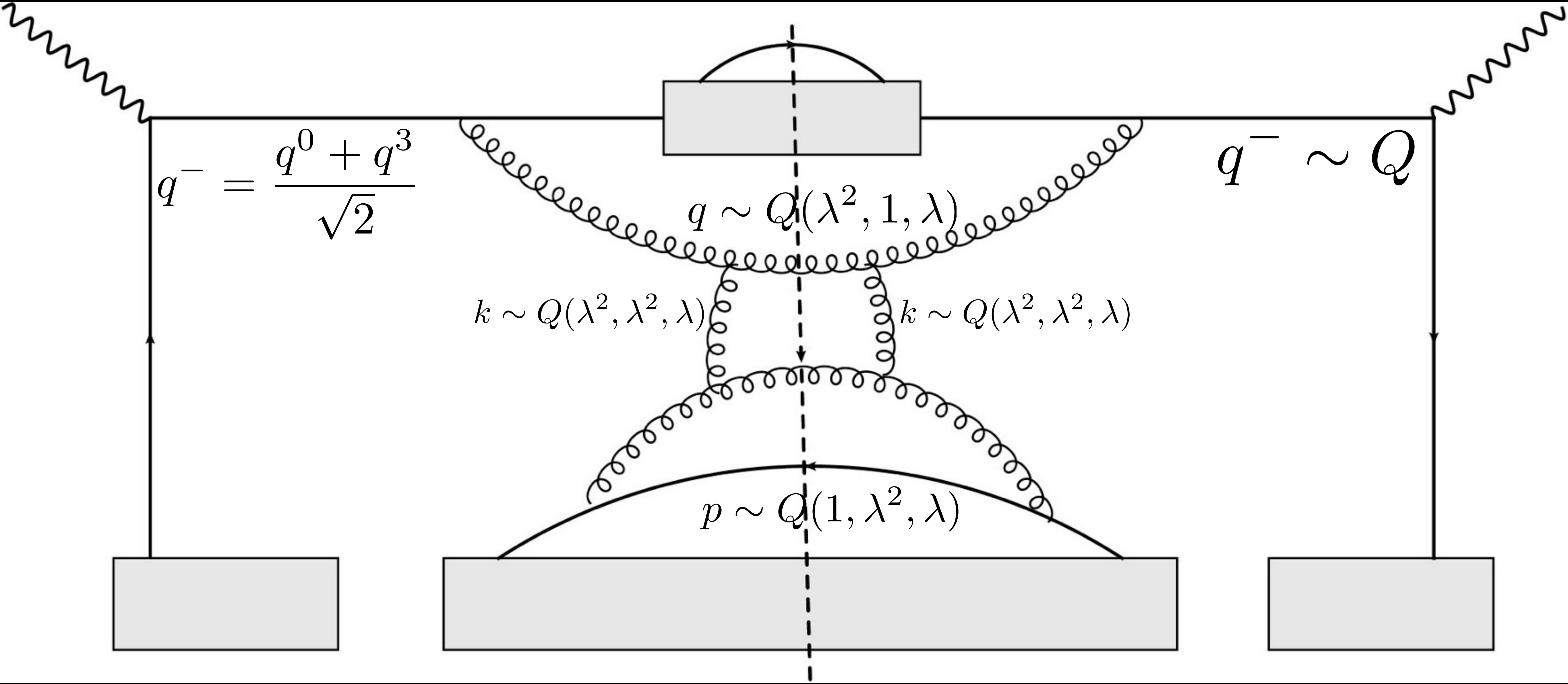


Q is the hard scale of the jet ~ E

$Q\lambda$ is a semi-hard scale ~ $(ET)^{1/2}, \lambda \longrightarrow 0$

$\hat{q}$ contains all dynamics below $Q\lambda$

A factorized picture

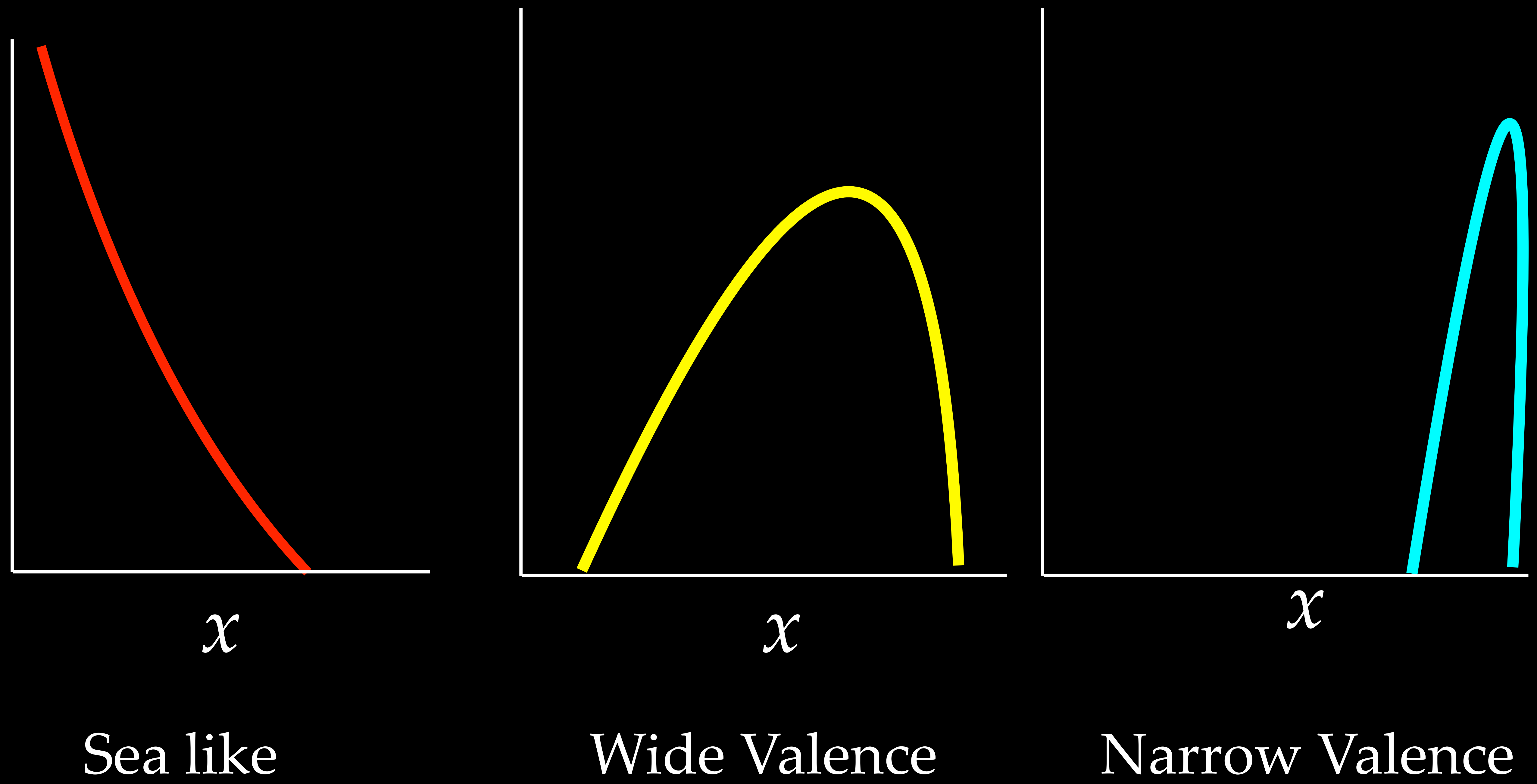


Q is the hard scale of the jet ~ E

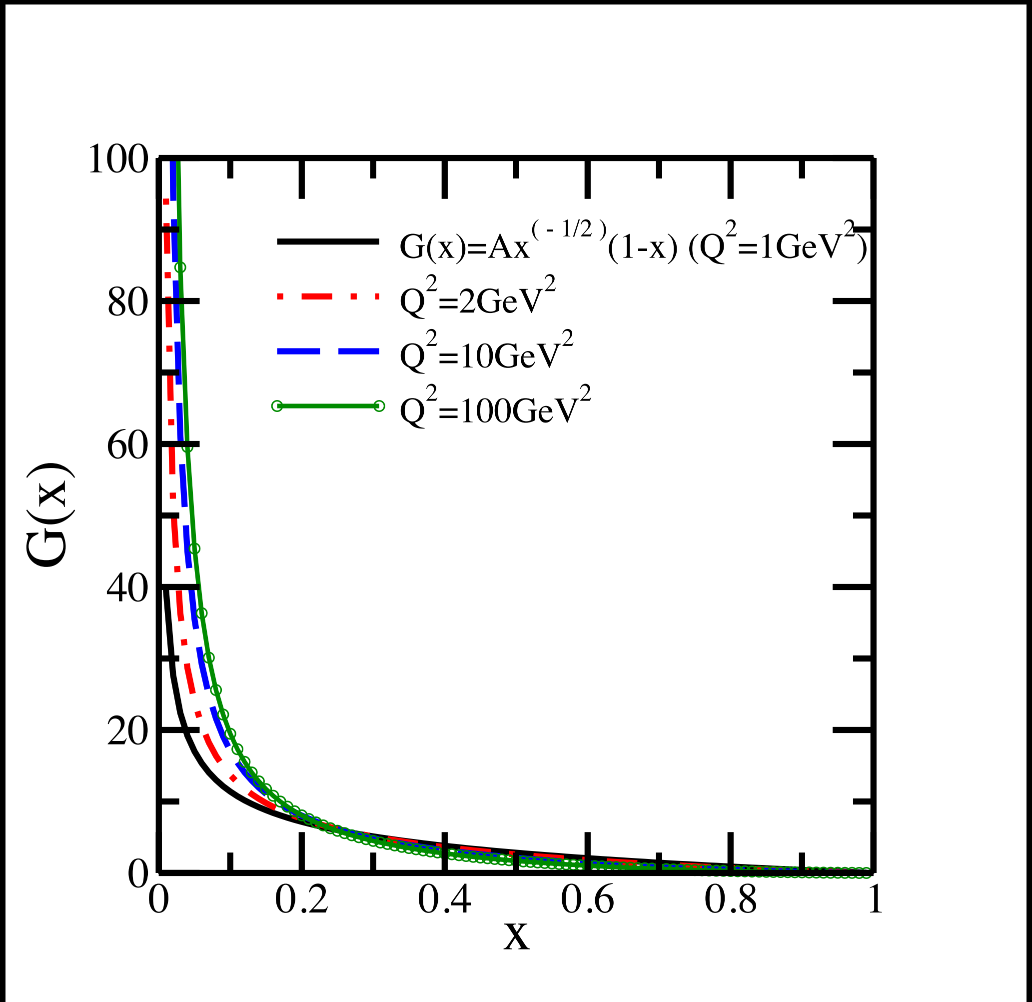
$Q\lambda$ is a semi-hard scale ~ $(ET)^{1/2}, \lambda \longrightarrow 0$

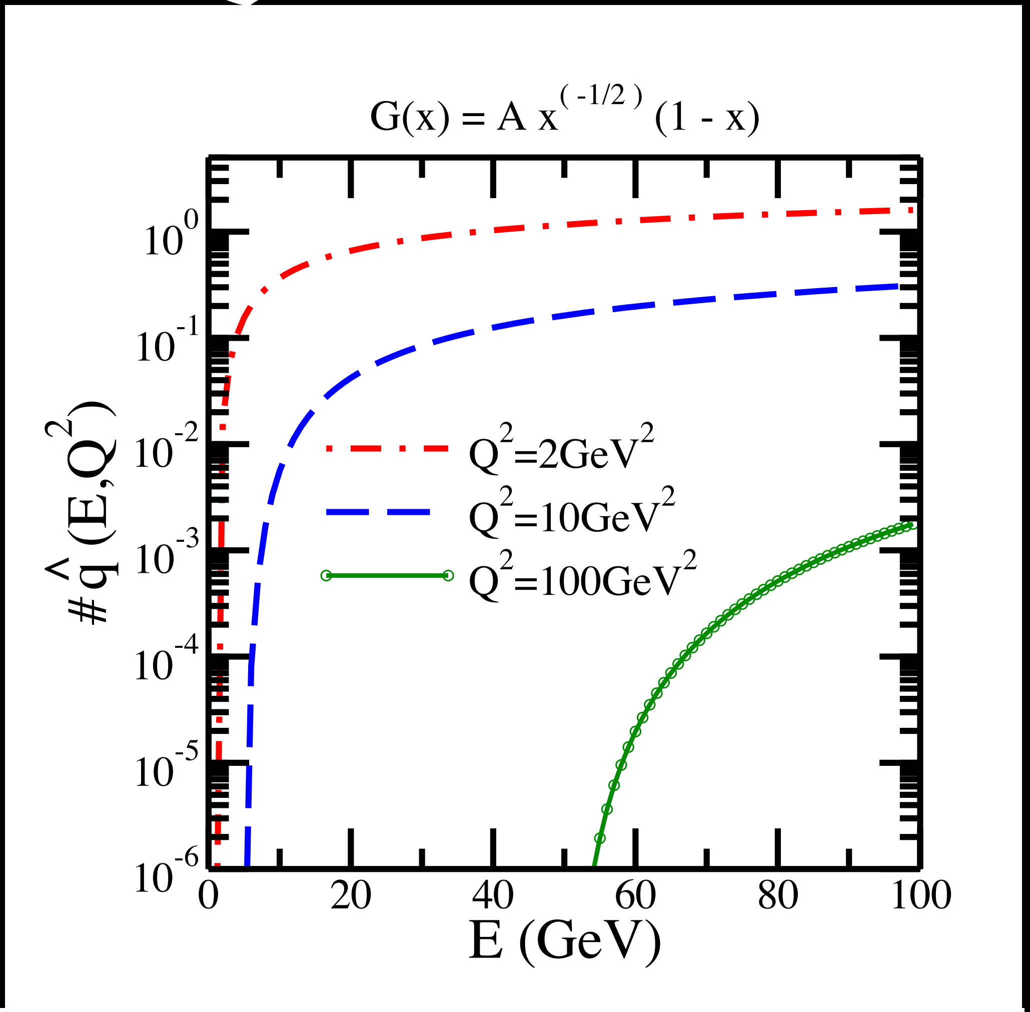
$\hat{q}$ contains all dynamics below $Q\lambda$

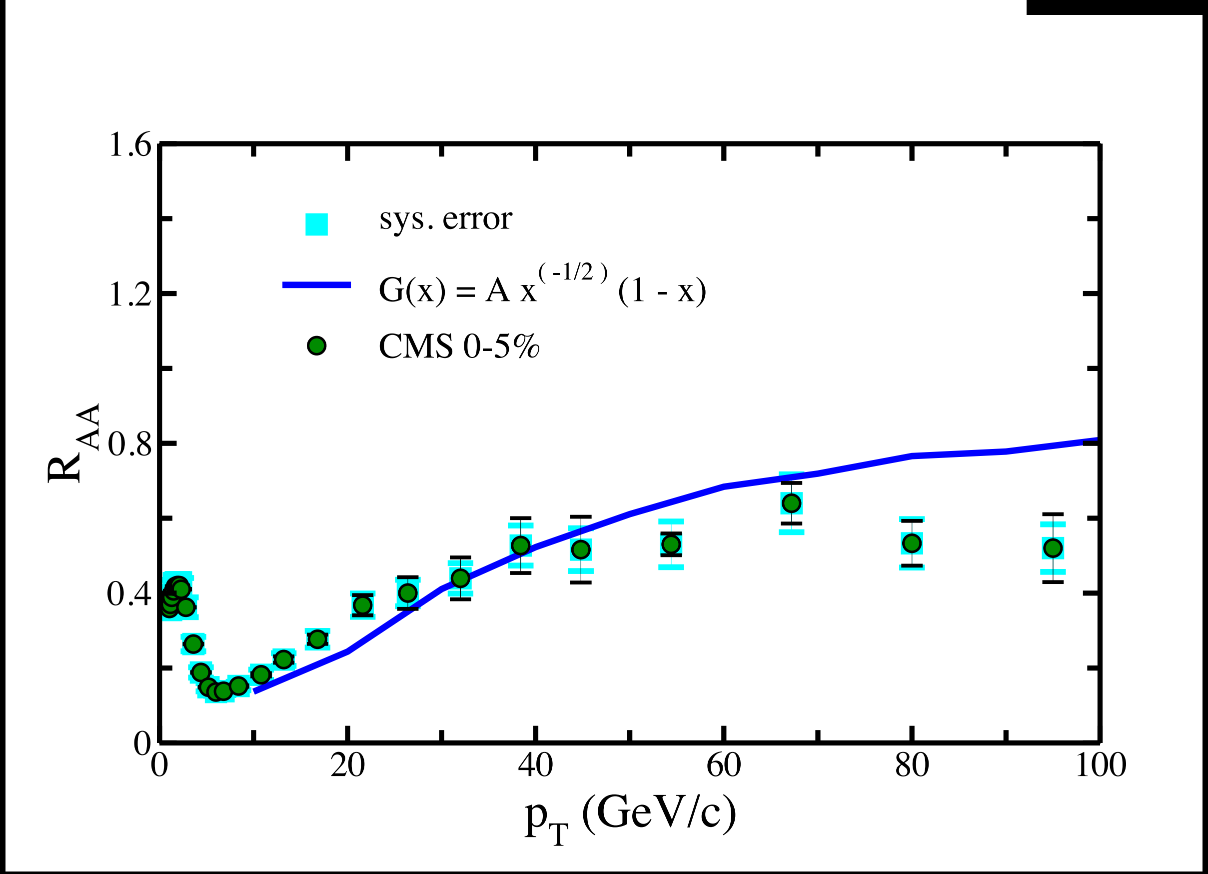
Input PDF at $Q^2 = 1$ GeV^2

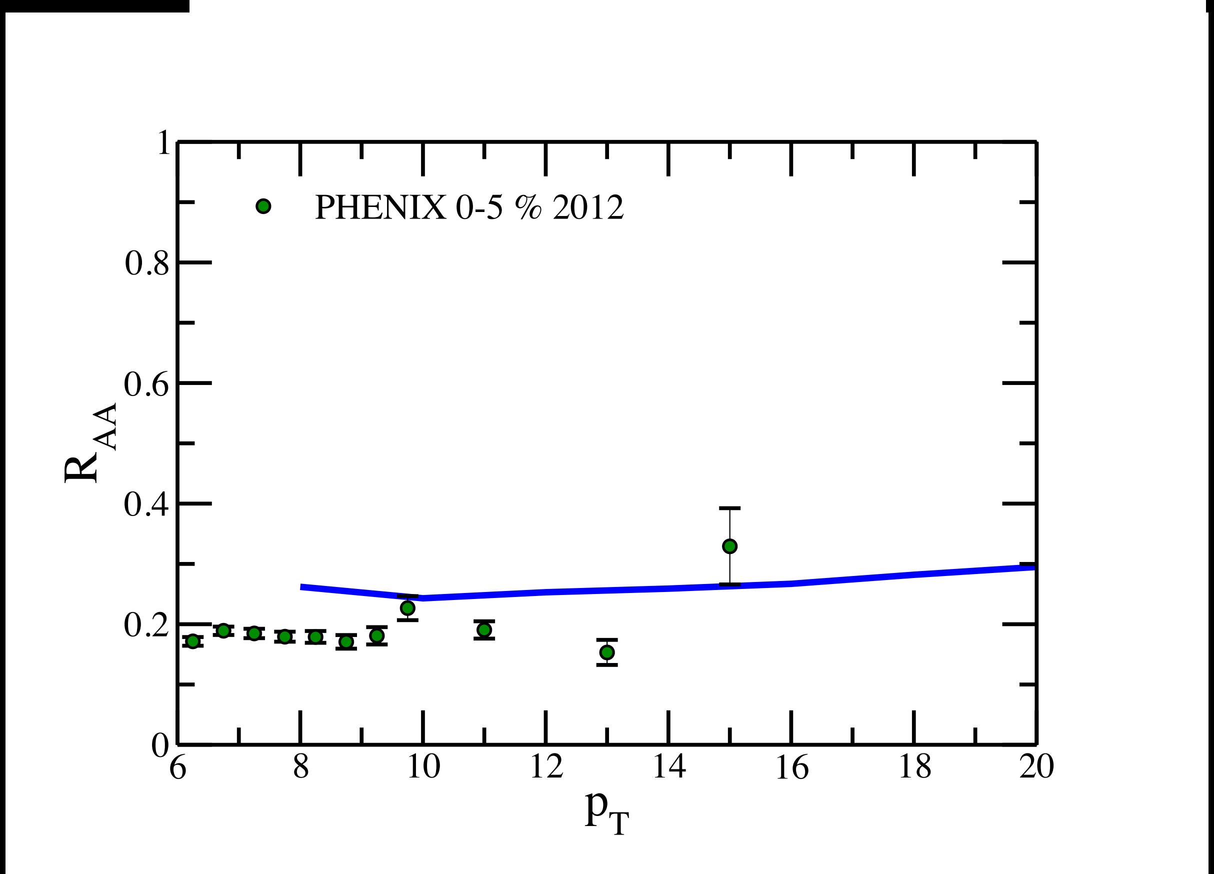


Sea-like PDF of the QGP

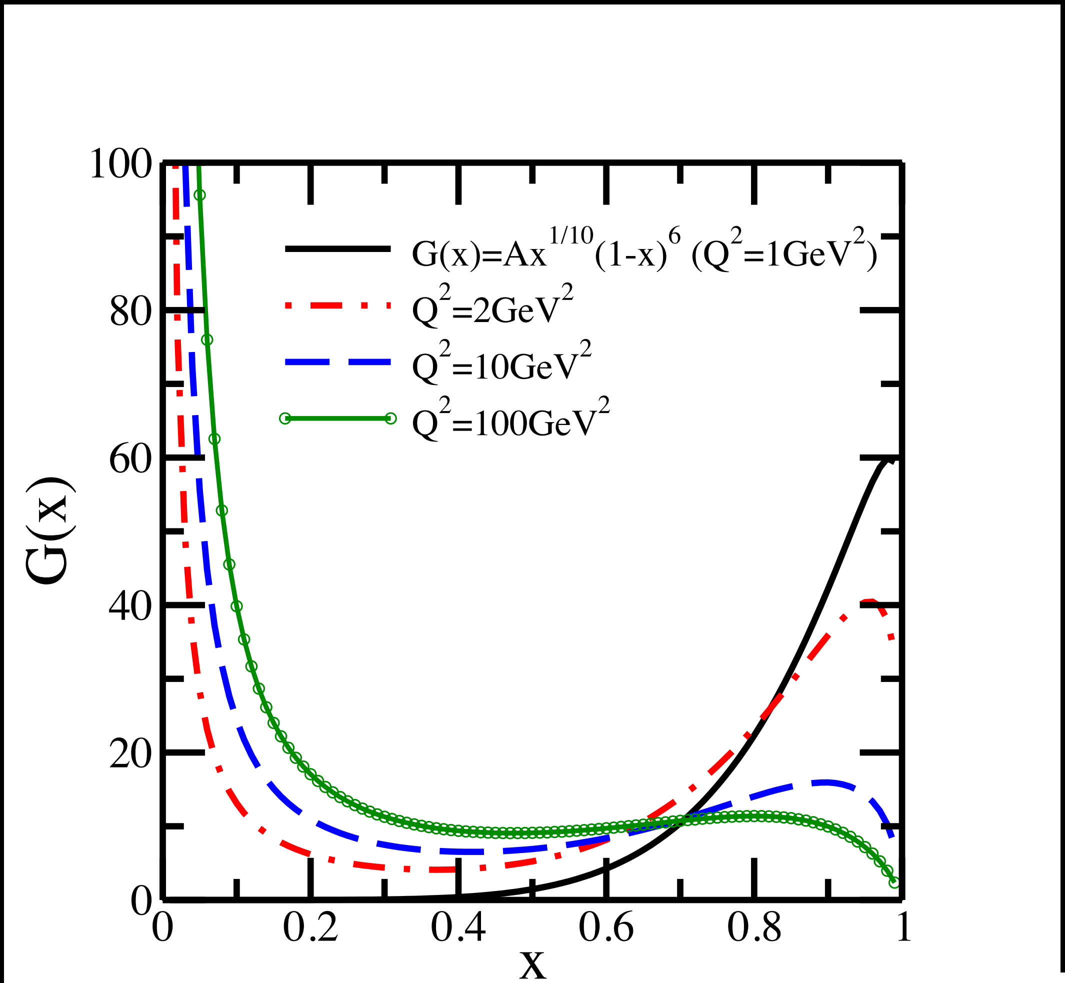


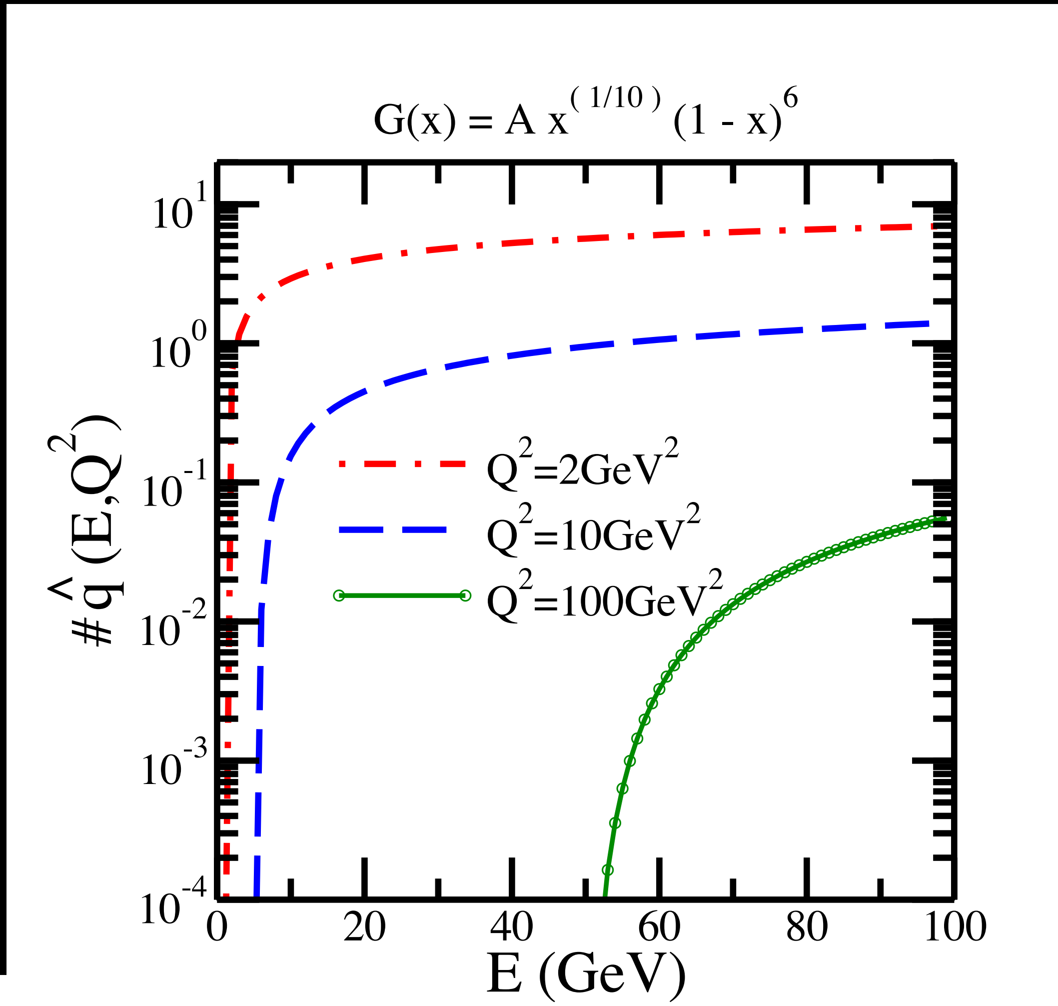


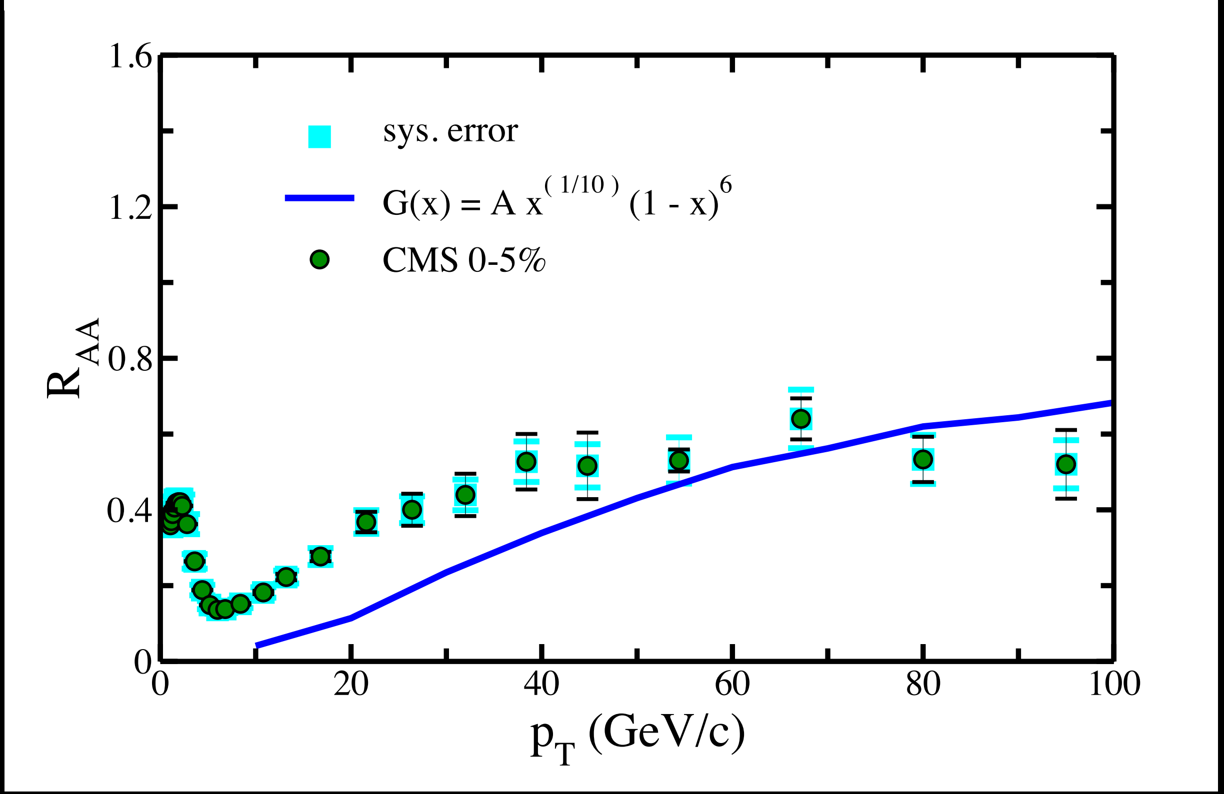


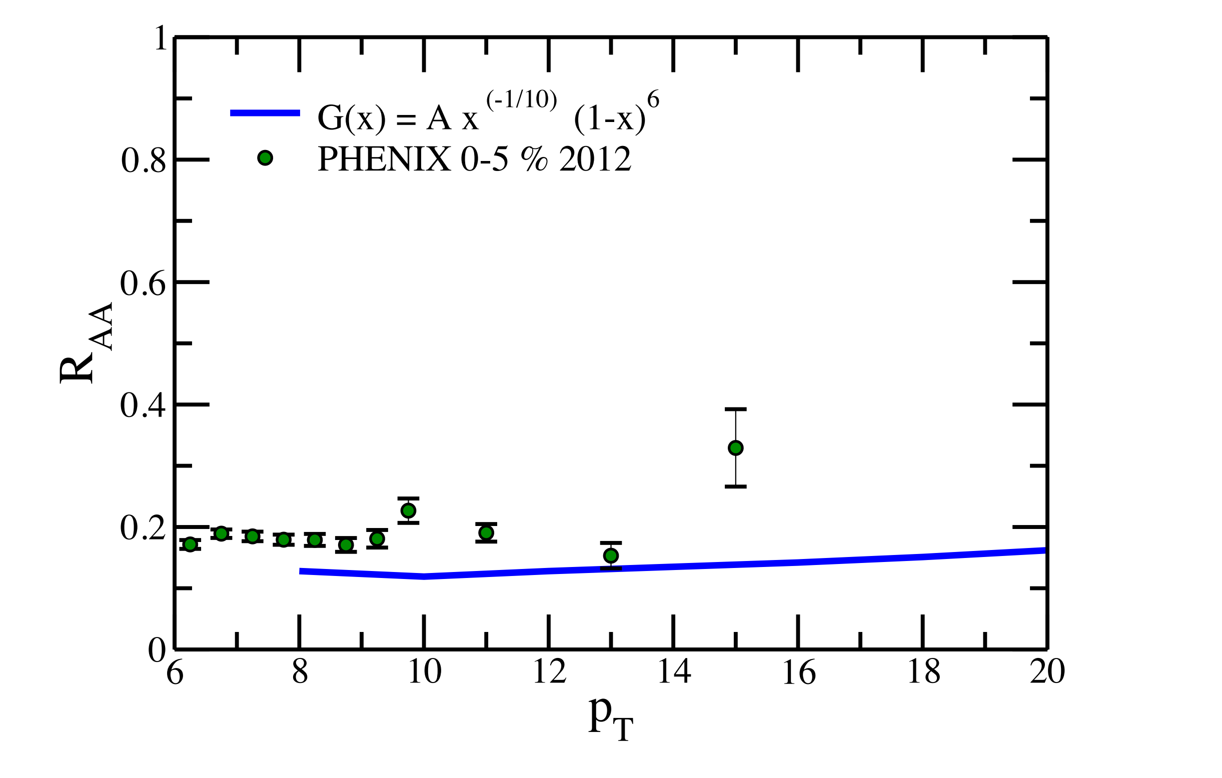


Narrow valence like PDF of QGP

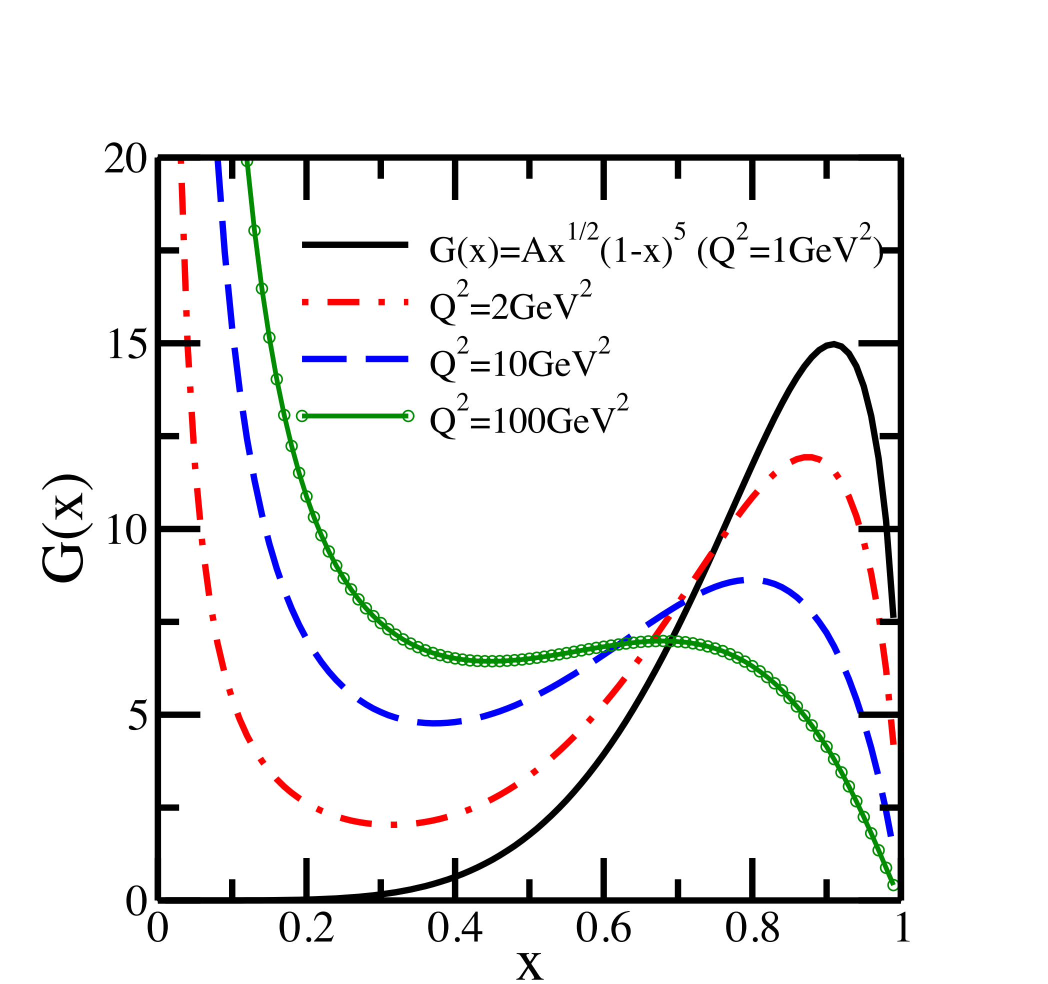


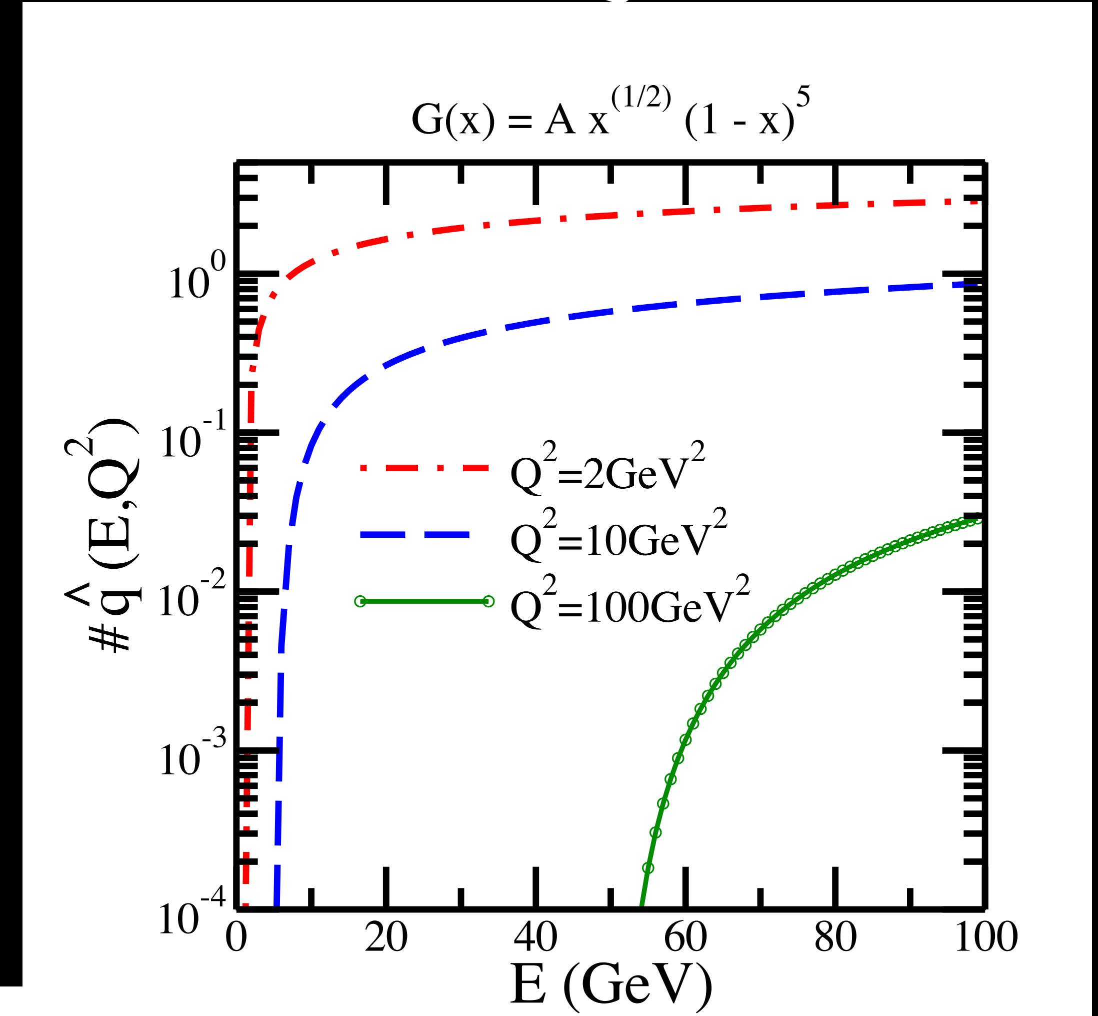


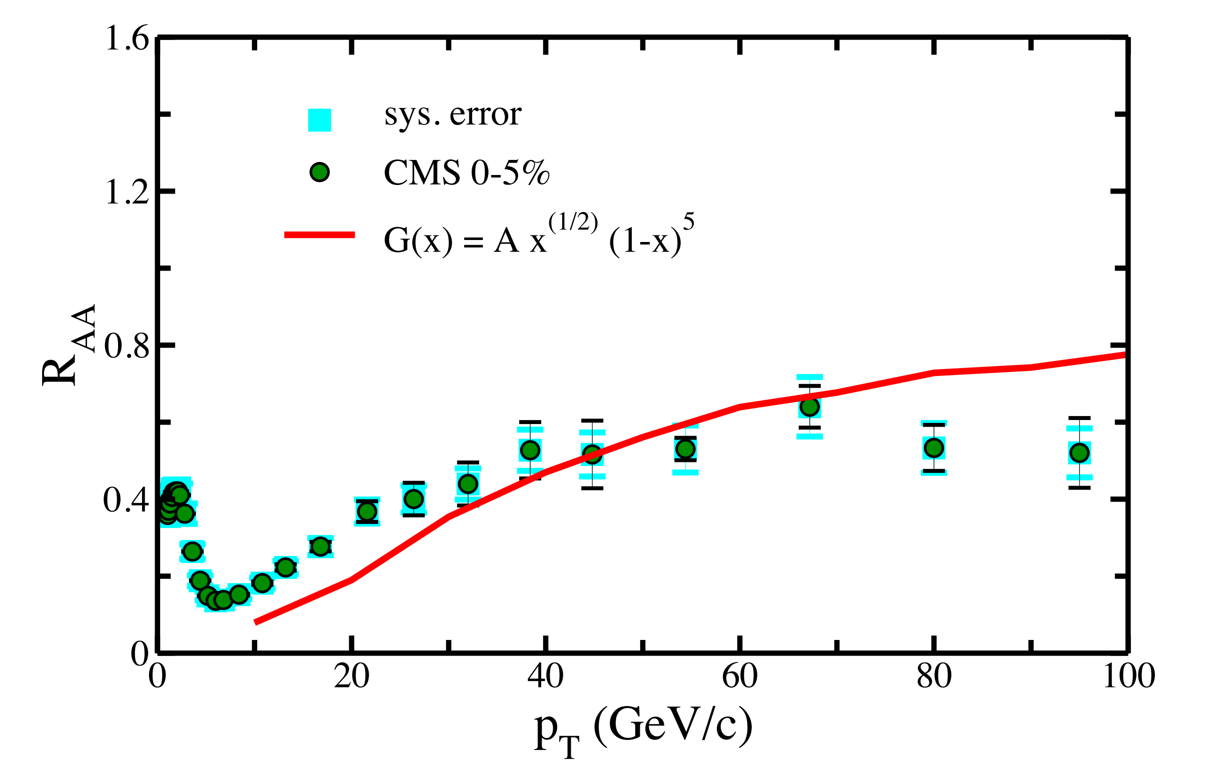


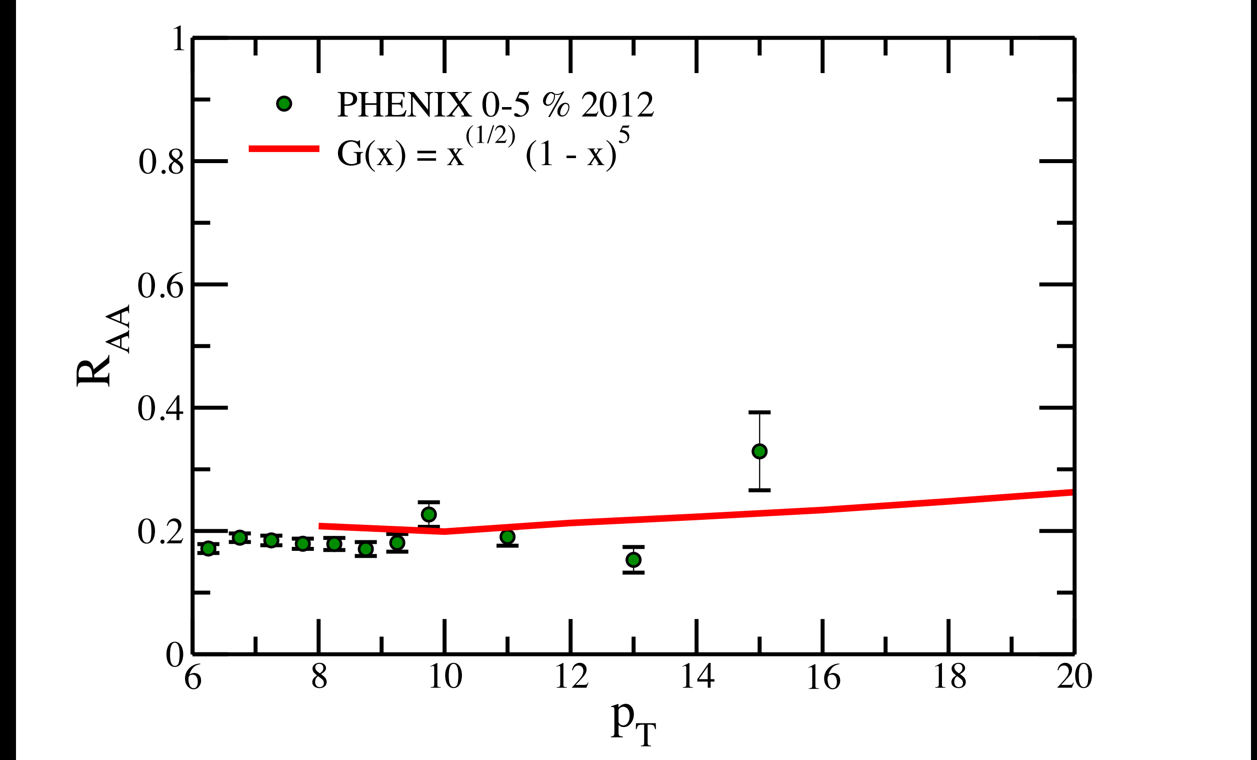


Wide valence like PDF of the QGP





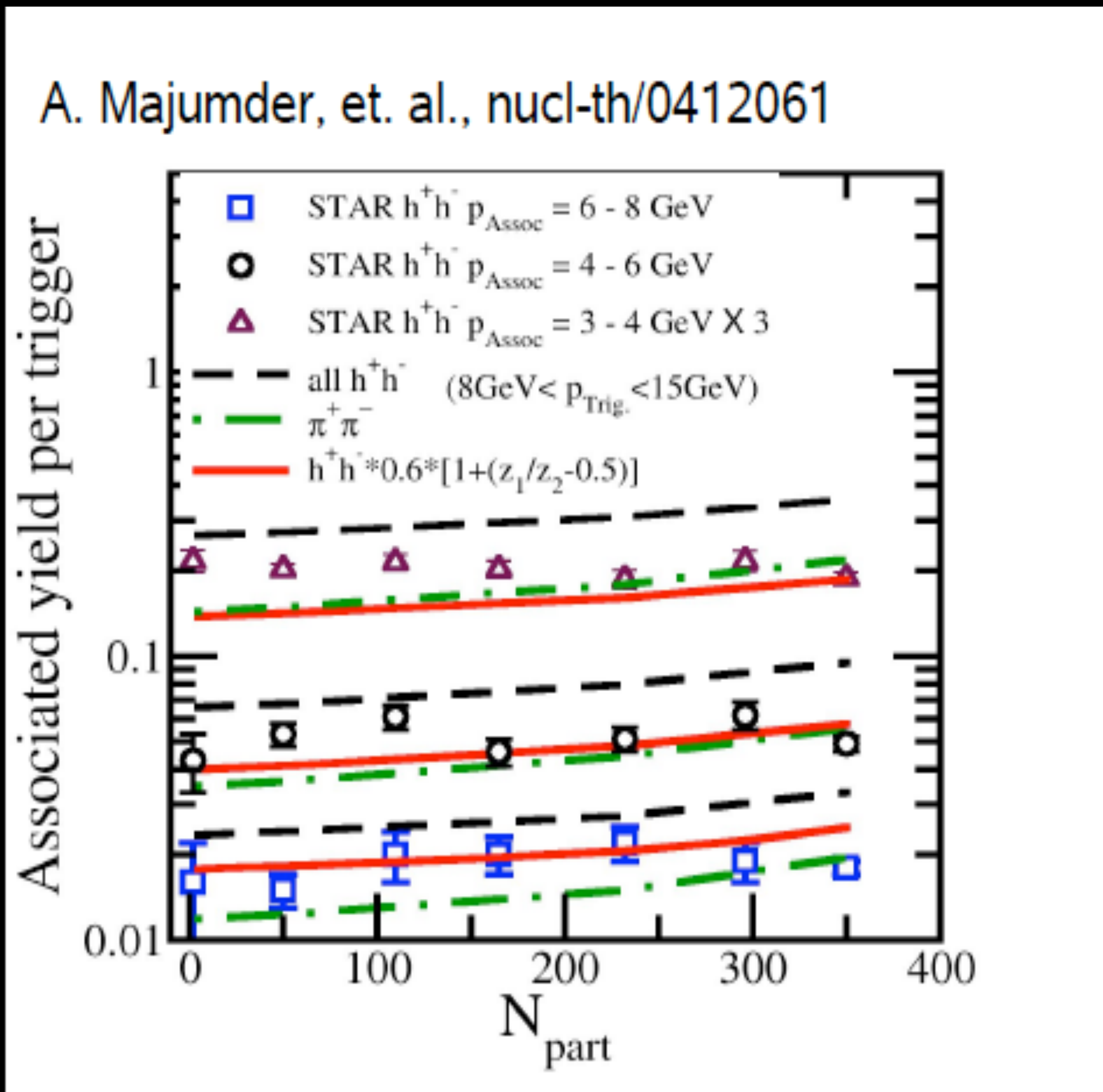


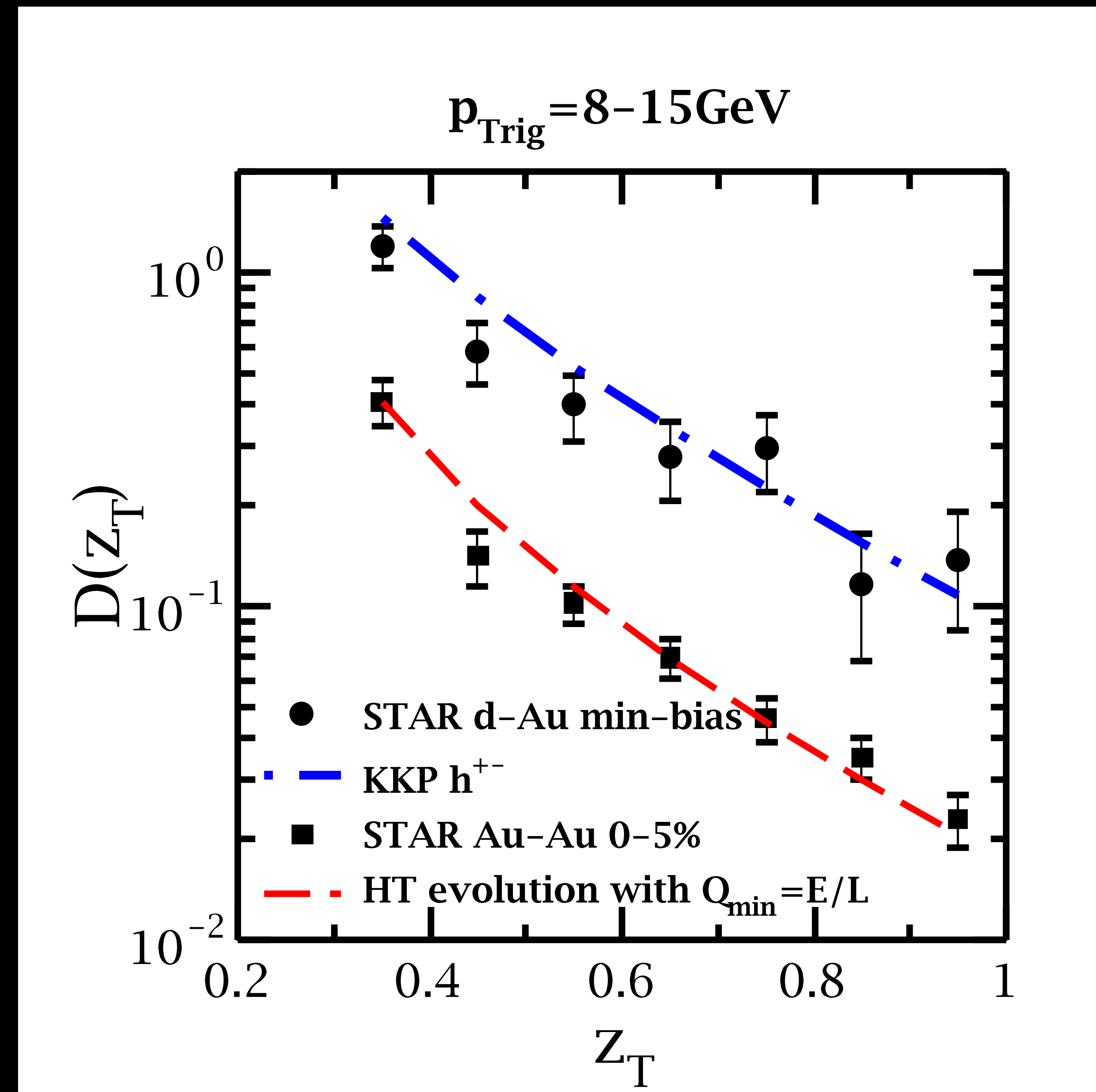


What does this mean?

- Possible resolution of the JET puzzle
- Based on consistent Q^2 evolution of $\hat{q}$
- Should have x evolution at high energy
- Will be done in reverse very soon, will get PDF's with bands (by Quark Matter !!!)
- Applying TMD systematics, may complicate this interpretation.

Near side and away side correlations





A wide range of single particle observables can be explained by a weak coupling formalism